STUDIES IN FLUIDIZATION

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CHAPTER I

INTRODUCTION

Until World War II there was little application of fluidized beds by industry; consequently, very little information about fluidized beds was published. However, during this period many fluid-catalytic cracking units were built in this country. In 1947 literature about fluidization began appearing, and since that time a number of articles have been published.

Despite this, much work still needs to be done in the field of fluidization. There seems to be a growing interest in applying fluidized beds to additional processes. One recent application is the use of a fluidized bed in the production of SO_2 from low-grade sulfur ore (1).

Terms relating to fluidization are found in tabulated form in Appendix A. "A fluidized bed is a mass of solid particles which exhibits the liquid characteristics of mobility, hydrostatic pressure, and an observable upper free surface or boundary zone, across which a marked change in concentration of particles occurs." (2)

Figure 1 shows a typical fluidized system including both a reactor and a regenerator. Dense phases are found in the lower portions (above the grids) of the reactor and regenerator, and dilute phases are found in the disengaging sections of the reactor and regenerator. These two phases can also be found in the transfer lines between the two vessels. For example, a dense phase exists in the transfer line from the bottom of the standpipe to the bottom of the reactor.

As was previously stated, there have been many articles published about fluidized systems since 1947. They can be divided into three main groups: One, heat transfer in fluidized systems (20, 34, 35, 31, 13, 11); two, mass transfer in fluidized systems (21, 10, 29, 9, 30); and three, the general characteristics of fluidized systems (38, 18, 39, 36, 23, 22, 19, 6, 17, 14, 4, 36, 16, 5, 28, 26, 33).

The general characteristics of fluidized systems can again be divided into three main classes: One, the uniformity of fluidization and its measurement (32, 27, 24); two, the pressure drop in transfer lines (7, 3, 8); and three, basic observations about fluidized beds in general (relating particle size, size of equipment, gas rates, etc.).

Again, this last group about basic observations in fluidized systems can be sub-divided into several groups, and one such sub-division shall be the subject from this point.

When solid particles fall from the regenerator (or reactor) into the standpipe (see Figure 1), they come from a turbulent phase. During this fall in the standpipe the

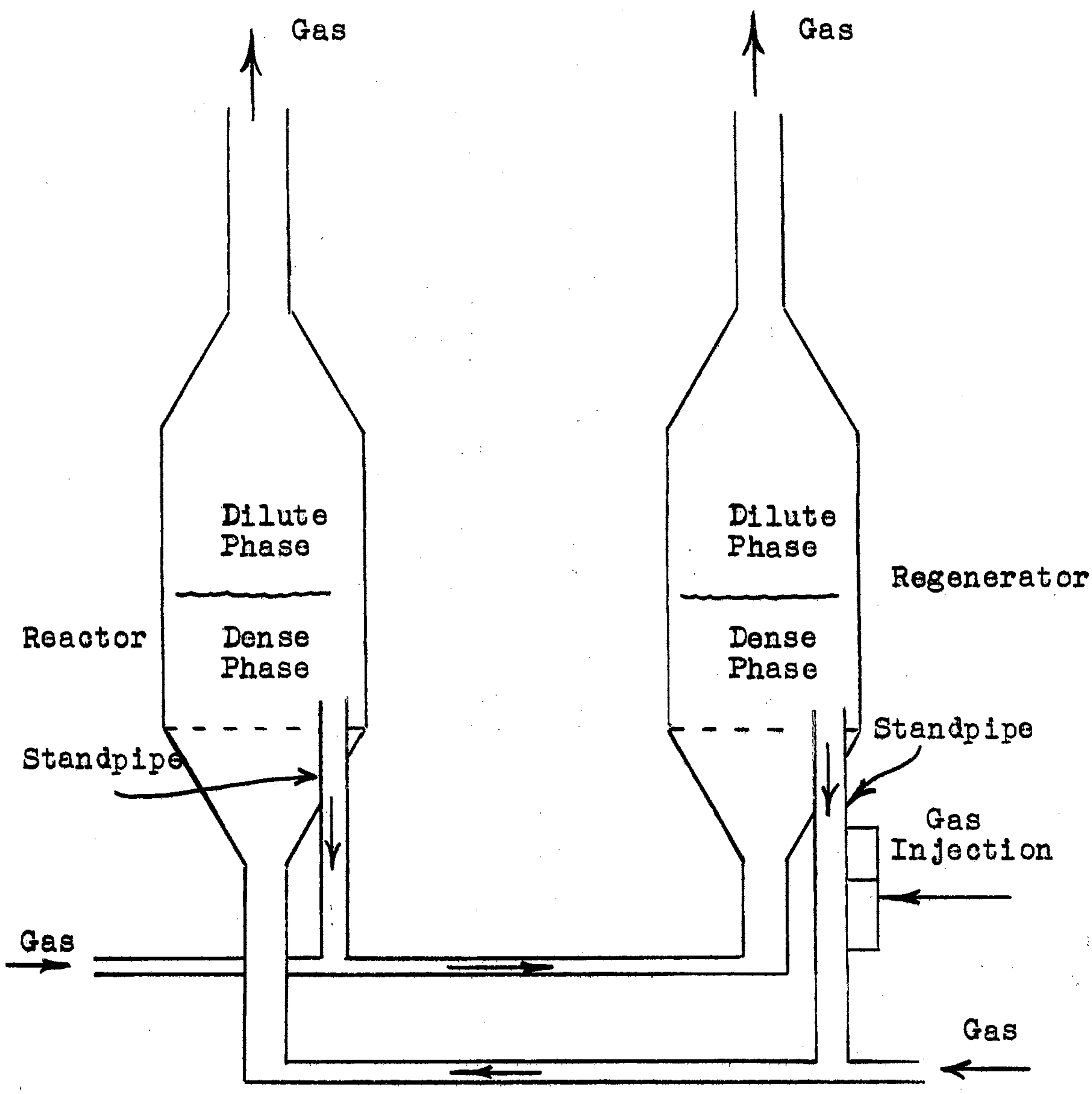


FIGURE 1 FLUIDIZED SYSTEM

particles are partially aerated. As they approach the top of the bed, which is moving downward in the standpipe, rapid deaeration takes place. Dickman and Forsyth (5) developed a method whereby the deaeration characteristics of fluid-cracking catalyst can be predicted in the laboratory. A correlation is found between their observed results and commercial operation. (From this point on, the terms "catalyst" and "solid particles" are synonymous.)

In plant operation, aeration gas is added at intervals along the standpipe to control the deaeration rate and to reduce unsteady operation, such as bumping and slugging, in the standpipe. (From this point on, "aeration gas" and "dispersing medium" are synonymous.) It is known that the catalyst forms large masses in some commercial standpipes. This causes serious bumping (i.e., forming large falling masses). In commercial operation where there are hundreds of pounds of catalyst being transported, considerable forces are built up when these masses form and then fall.

The purpose of this investigation was to determine the effect of two variables on the flow of catalyst in a standpipe. These were—, the type of injection points along the standpipe for the aeration gas; and the minimum amount of injection medium required to keep the solid particles flowing smoothly in the standpipe.

CHAPTER II

THEORY OF FLUIDIZATION

The theory of fluidization is still in the formative stage despite the number of correlations in the literature. In the succeeding sections these correlations are presented and their application discussed.

Pressure Drop

One of the simplest correlations in fluidization is a correlation of pressure drop as a function of fluid velocity.

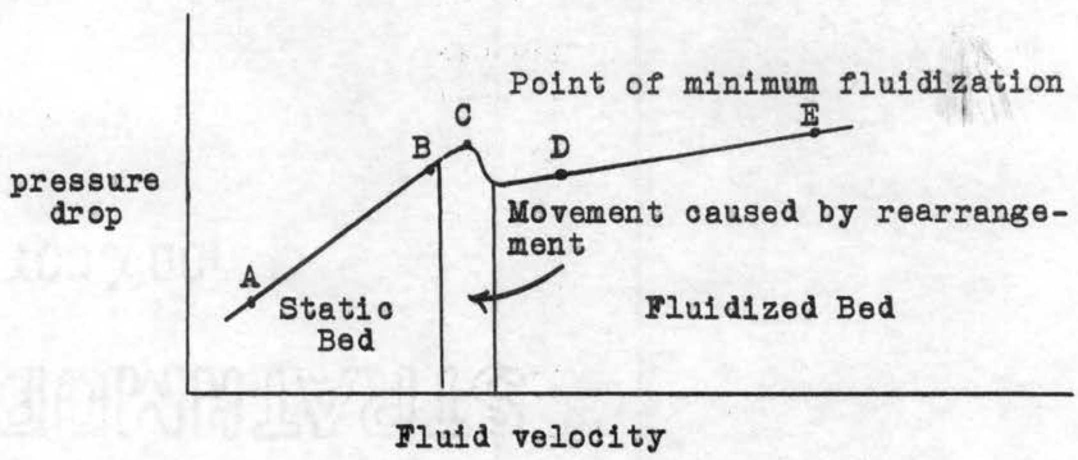


FIGURE 2. PRESSURE DROP AS A FUNCTION OF FLUID VELOCITY

From observation, we find that as the fluid velocity increases the pressure drop increases. Starting with low velocities, there is a steady pressure buildup. Then point C, called the point of minimum fluidization, is reached. At Point B the solid particles begin movement. This movement is actually a readjustment of the particles to allow a maximum amount of free space for the injected medium. Instability of the bed increases until point C is reached. Any additional increased flow of the gas will cause fluidization to start. This additional increase in gas rate causes the condition known as "minimum fluidization". With the addition of more air all the particles are in motion. The pressure drop between A and B is caused by the resistance to flow through a packed bed. This behavior is dependent on the particle size and on the density difference between the particle and the dispersion medium.

There are two forces acting on a fluidized bed. One force is acting to raise the particles, and the other force is acting to settle the particles. The force tending to raise the particles consists of two things--the buoyant force and the friction force. The buoyant force comes from the injection medium, and the friction force comes from the gas passing over the solid particles. The force keeping the particles in the static state is the weight of the particle, or the pull of gravity on each particle mass.

When these two forces are equal, the following equation can be written:

$$\underbrace{\frac{g}{g_c}(1-\epsilon)(L)(A)(\rho)}_{\text{Force Up}} + \underbrace{(-\Delta P_f)(A)}_{\text{Force up}} = \underbrace{\frac{g}{g_c}(1-\epsilon)(\rho_s)(L)(A)}_{\text{Force down}}$$

or:

$$-\Delta P_f = L\ (1-\epsilon)(\rho_s-\rho)(\frac{g}{g_c}) \qquad (1)$$

Leva (14) states that for laminar flow the following equation is correct:

$$P = \frac{(1-\epsilon)^2}{\epsilon^3} \qquad (2)$$

There are two basic forces of fluidization: the weight gradient through the bed $(1-\epsilon)\ (\rho_s-\rho_g)$ and the viscous drag of the fluid acting upward to disperse the bed $(^{\Delta P}/L)\ (g)$, the latter called the fluid flow gradient. There appears to be a third force or combination of forces, the net effect of which is to retain the bed in a compacted state. Such forces may be either electrostatic or fluid dynamic in origin, or both.

Froude Number Correlations

Before one progresses further in the study of fluidization, a distinction must be made between particulate and aggregate fluidization. (See Appendix A for definitions.) The data of Wilhelm and Kwauk (37) suggests that a correlation between particulate and aggregate fluidization can be derived by means of the dimensionless Froude Number.

$$N_{Fr} = {}^{v^2}/dpg \qquad (3)$$

Lowenstein (18) presents a nomograph for rapid estimation of fluidization velocities. If the particle diameter is plotted as a function of Froude Number a graph similar to Figure 3 results.

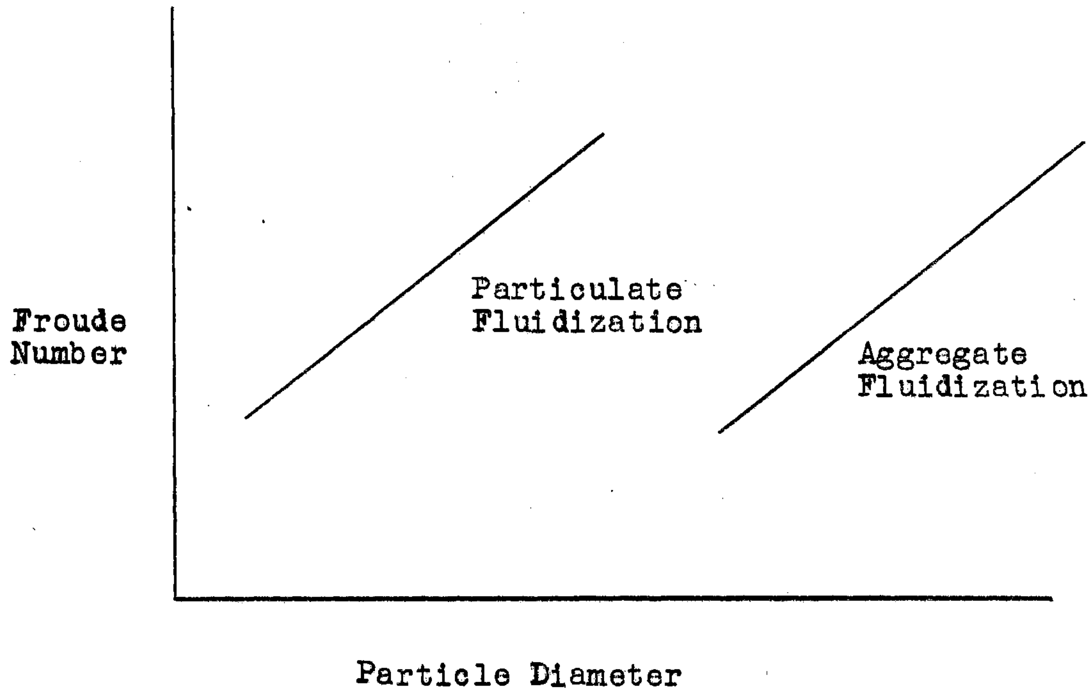


FIGURE 3. FROUDE NUMBER AS A FUNCTION OF PARTICLE DIAMETER

Porosity

The porosity is given by the following equation:

$$\epsilon = \frac{L-L_o}{L} \qquad (4)$$

Just before fluidization is reached, the bed swells, and the bulk density decreases. This is followed by the condition known as fluidization.

Olin and Patterson (25) found a relation between porosity and Reynolds Number.

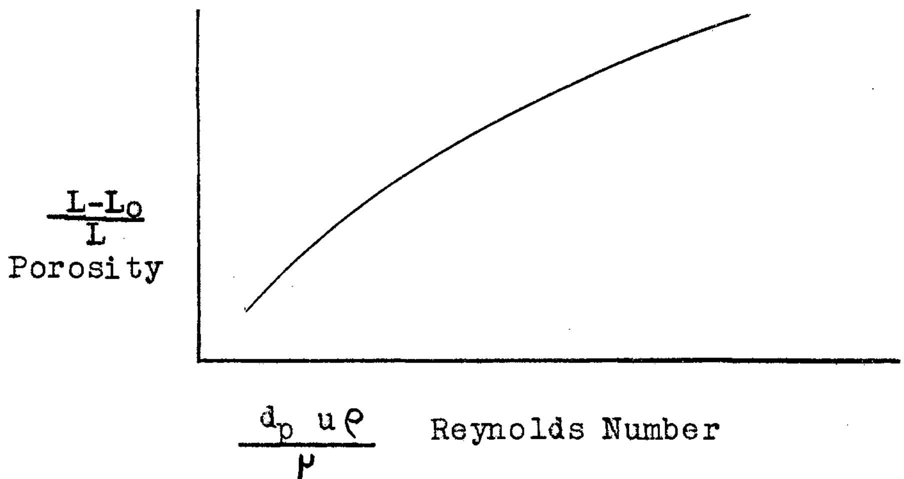


FIGURE 4. POROSITY AS A FUNCTION OF REYNOLDS NUMBER

Over the range of their data, using clean round sand, the following empirical relation holds:

$$\frac{L-L_o}{L} = \frac{(0.033)}{(d_p^{0.36})\ (Re^{0.14})} \tag{5}$$

If the log porosity as a function of log Reynolds Number were plotted on a bed undergoing fluidization a graph similar to Figure 5 results.

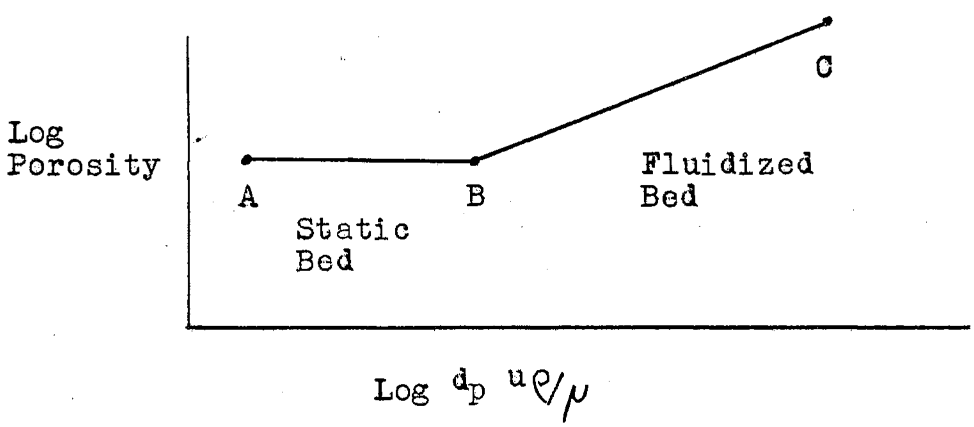


FIGURE 5. LOG POROSITY AS A FUNCTION OF REYNOLDS NUMBER

With the data of Wilhelm and Kwauk (37), line BC can be formed by extrapolation. Point C represents the free settling velocity of the individual particles.

Dimensionless Relations

Excluding shape factor (which is discussed in the section entitled Relative Velocities), the following variables are important in a fluidized system:

$$(g\Delta P),\ d_p,\ L, \mu_o\ \ (\rho s-\rho f)g\ ,\ s,\ \mu$$

Definitions are found in the table of nomenclature. These variables, with the additional dimensionless variable, ϵ, were formed by Wilhelm and Kwauk into four dimensionless groups as follows:

$$d_p \frac{u_o \rho_s}{\mu} = N_{Re} \tag{6}$$

$$1/2\ \frac{d_p^3 \rho_s\, g}{\mu^2} \left(\frac{\Delta P}{L_o}\right) = K\Delta p \tag{7}$$

$$1/2\ \frac{d_p^3 \rho f g}{\mu^2} (\rho s - \rho l) = K'\Delta p \tag{8}$$

$$\frac{L-L_o}{L} = \epsilon \tag{9}$$

Equation seven is the product of a modified friction factor for the flow of fluids through granular beds by the square of the modified Reynolds Number. Equation eight is the product of the drag coefficient of particles settling under the influence of gravity and the square of the modified Reynolds Number. It may be noted that the usual 4/3 in the drag coefficient is changed to 1/2 so that $K\Delta p$ and $K'\Delta\rho$ may be referred to a common scale (see Figure 6).

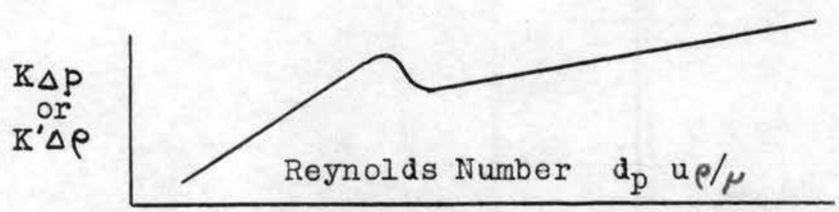


FIGURE 6. FRICTION FACTOR AS A FUNCTION OF REYNOLDS NUMBER

Friction Factor Relations

A correlation by Olin and Patterson (25) relates friction factor, Reynolds Number, and the particle size. the term $\epsilon^3/(1-\epsilon)^2$ is used in the friction factor to correct for voids. The relation shows that for a constant Reynolds Number, as the particle size increases, the friction factor increases (Figure 7).

$$F_f = \frac{\Delta p \; d_p \; G \; g \epsilon^3}{2 G^2 \; L \; (1-\epsilon)^2}$$

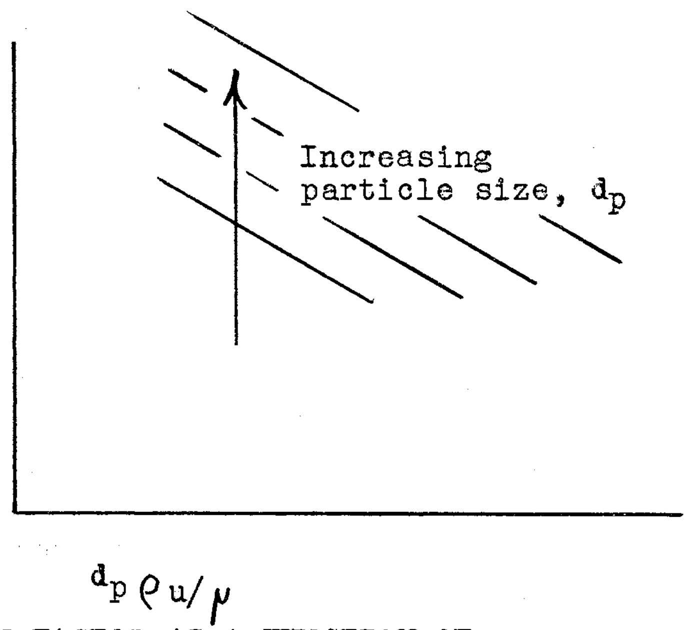


FIGURE 7. FRICTION FACTOR AS A FUNCTION OF REYNOLDS NUMBER

Relative Velocities

In a confined fluidized bed the net velocity of the particles will be zero. When the bed has a net motion with respect to the fluid, the velocity is the difference $(v-v_p)$ in the velocities. Therefore, in a bed where the solid particles are moving downward, the correct modified Reynolds Number will be:

$$N_{Re} = \frac{d_p \; (v-v_p) \, \rho}{\mu} \tag{10}$$

Toomey and Johnstone (33) found a relation between the energy required for fluidization and the terminal settling velocity of spherical particles.

$$\ln \frac{v^g}{v^v} = \frac{1}{(Kd_p 0.5 - k)} \frac{\Delta p^{ke}}{\Delta p^{mf}} \qquad (11)$$

Shape Factors

Leva (16) has presented data that gives a correlation for shape factors. The equation derived is for all particles.

$$\lambda = 0.205 \frac{A}{V} d_p 2/3 \qquad (12)$$

For spheres λ is equal to 1.0 and for all other particles λ is less than 1.0. It is to be noticed that shape factor and sphericity are the same thing.

Segregation Tendency

One of the advantages of a fluidized bed is the uniformity of the solid particles with relation to the total gas stream. However, due to channeling or slugging conditions, the bed can become less uniform than a fixed bed. This condition can be visualized by using a sample of extreme particle sizes. It takes more air to suspend a very large particle than it does a very small particle. In commercial operations the solids "wear out", thus becoming increasingly smaller (this varies in operation) until they are carried off by the fluidizing medium.

Lapple (12) states that a bed of free flowing particles with a high segregation rate will exhibit predominantly "aggregative" fluidization, but with a low segregation rate the bed will exhibit mainly "particulate" fluidization.

By use of the Carman-Kozeny correlation Lapple obtained the following equation:

$$u_o = \frac{L_f \, (\rho s-\rho f)(\epsilon 2-\epsilon 1) \quad (g_c) \, (\epsilon 3)^3}{a^2 \mu \; 5 \; L_1} \qquad (13)$$

Segregation is represented by u_o.

Several conclusions may be drawn from Equation (13). These conclusions are taken from Lapple (12):

"1. The segregation tendency is inherent in any fluidized bed and is self-accelerating. This conclusion is drawn from the dependence of u_o (segregation rate) on $(\epsilon 2-\epsilon 1)$; as segregation proceeds $\epsilon 2$ increases and $\epsilon 1$ decreases; consequently their difference increases and thereby the segregation rate also increases. The limit is reached if ϵ_2 becomes 1.0 and ϵ_1 becomes the voidage of the settled bed. When this situation exists, stable channels pass through a stagnant bed, and segregation has proceeded to completion. This situation normally occurs only with materials which are not free-flowing.

2. The segregation rate is greatest at the bottom of the bed since u_o is proportional to L_f. As a corollary, deeper beds should exhibit greater segregation and correspondingly poorer quality of fluidization.

3. Liquid fluidized beds have much smaller segregation rates than do gas fluidized beds, because of the roughly fifty-fold higher viscosity and the smaller density difference. This is believed to be the principal reason for

particulate fluidization in Wilhelm and Kwauks water fluidized beds and aggregative fluidization of the air fluidized beds.

4. High density particles have correspondingly high segregation rates. As a corollary, decreasing the effective particle density by using hollow or vesicular particles, or by using porous flocs, should decrease the segregation rate.

5. The smaller the particle, the larger its specific surface and consequently the smaller its segregation rate. Unfortunately, decrease of particle size is often accompanied by decrease in the free flow quality of a powder, which may offset the advantages of lower segregation rate."

Viscosity Relationships

The data of Dickman and Forsythe (5) shows a correlation between viscosity and aeration rate (ft./sec.). This correlation is found in Figure 8.

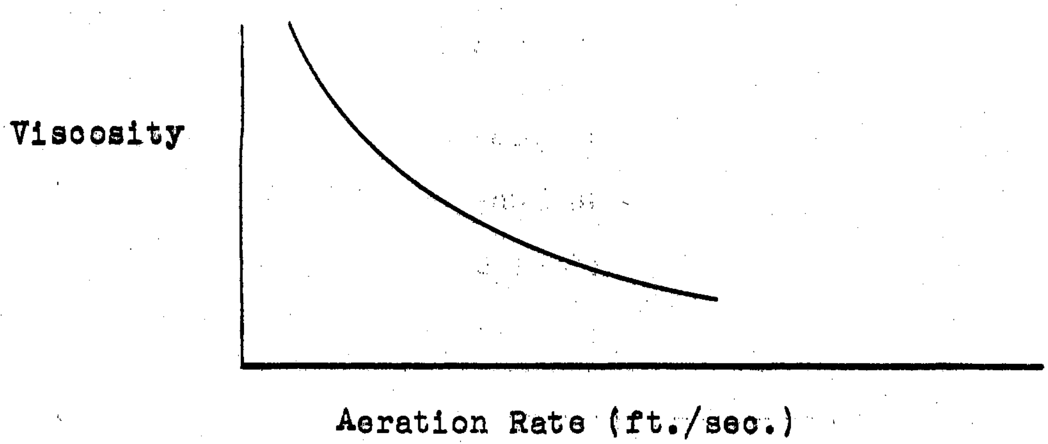


FIGURE 8. VISCOSITY AS A FUNCTION OF AERATION RATE

This concept relates changes in fluidity to changes in viscosity. The method is briefly: When the air in a fluidized system is shut off, the system "settles", and during this settling period, there is a change in viscosity (measured by a suspended Bookfield Viscometer). A correlation exists between this change in viscosity and the flow properties of the solids.

Application of Theory to Problem

The theory of fluidized beds has been presented in the first part of this chapter. To the present time, studies have been confined to vertical chambers of varying diameters with various means for injection of fluidizing medium. The present literature covers the various types of grid systems for the distribution of the gaseous medium by the system at different states of fluidization.

Little information is available for fluidized systems that would be encountered when the main body of solids is moving countercurrent to the gas. Application of this principle may be found in vertical transfer lines where the force of gravity is used to transport the solids. An analogous picture is a countercurrent extraction column. If slugs of gas and slugs of solids occur, they are detrimental to smooth operation.

A basic understanding of what actually happens in standpipes is essential before one proceeds. (From this point on the terms "column" and "standpipe" are synonymous.)

In most operations in the actual reaction vessel, the solids are in a turbulent state of fluidization. As they are withdrawn by spilling over into the standpipe, they go from a lean phase to a dense phase. They fall a short distance in a completely aerated state (lean phase). The laws governing free fall could apply in some cases. The particles then "hit" the main body of solids which is moving downward. In this interval of time, while "hitting", the solids undergo a rapid deaeration. If no fluidizing air is used to combat this rapid deaeration, the solid particles will form a mass and move down the bed.

Another problem enters when one considers flow in the standpipe. It is known that the type of grid system greatly determines the quality of fluidization. However, when gas is added to a standpipe, the downward flow of solid particles must not have an elaborate grid system to block flow. Therefore, gas will have to be added at points. It is assumed that the gas will diffuse toward the wall, and then the gas will act as though evenly distributed.

In this work air was used as the aeration gas, and entry was made at several points along the standpipe. Several methods of dispersing the gas were used: 1) running the tubes to the center of the standpipe and pointing upward; 2) extending the tube across the standpipe and having several outlets in the tube (this is like a portion of grid); 3) introducing the air through outlets in a cross arrangement at the bottom of the column. Figure 9 shows a conventional fluidizing column and standpipe.

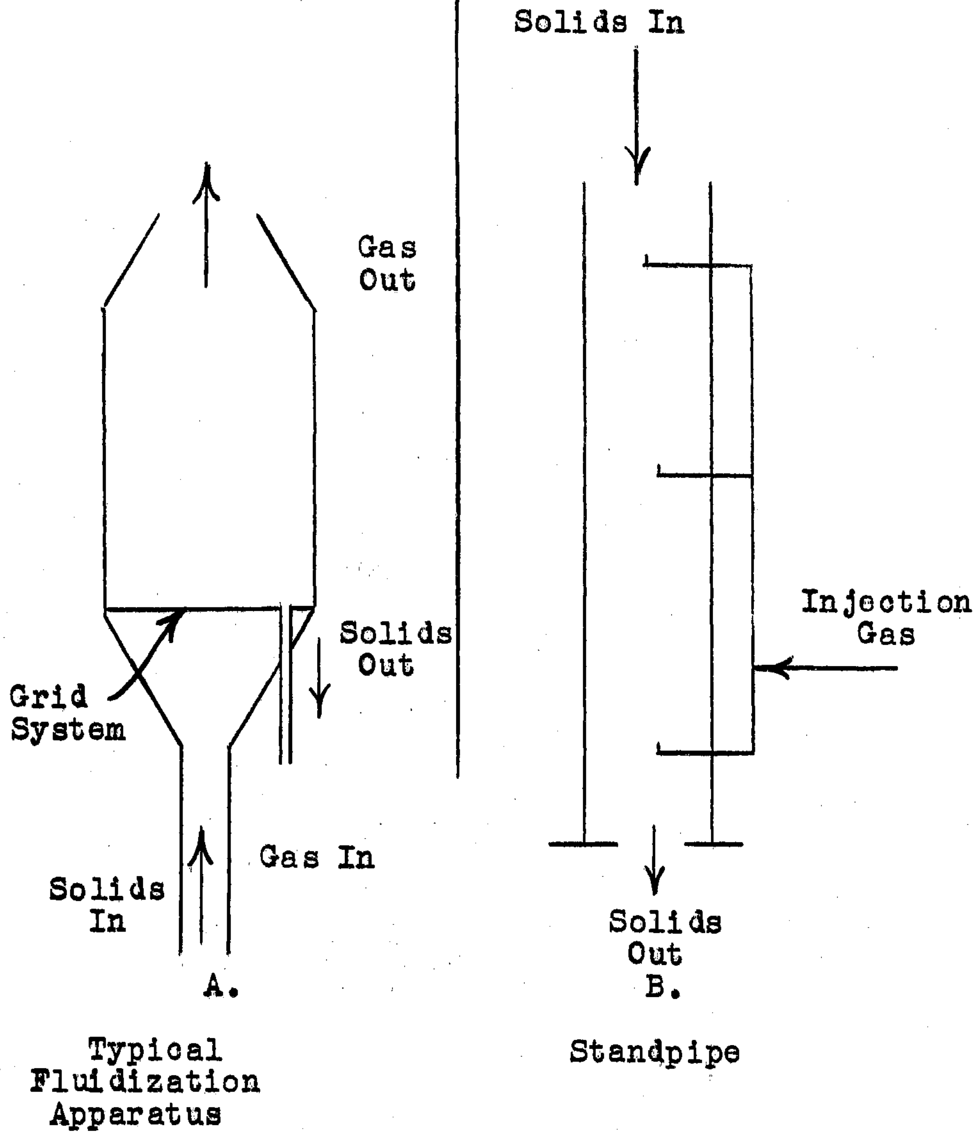


FIGURE 9. FLUIDIZED SYSTEMS

CHAPTER III

DESCRIPTION OF APPARATUS

Most work on fluidized beds has been done in confined vessels with a suitable gridwork at the bottom to disperse the gas. To study the downward flow of solids in standpipes, a false bottom must be employed. A column was chosen that had a large lenth-to-diameter ratio. The diameter was large enough so that wall effects were small. A column having a diameter of three and one-half inches was chosen.

The drawings of the column and associated pieces of equipment may be found in Appendix B. The column and its associated pieces of equipment will be described briefly.

The column was a plexiglass pipe five feet high, three and one-half inches inside diameter, and one-fourth of an inch thick. Plexiglass was chosen so that visual observations could be made. Eleven one-half inch holes were drilled in one side of the pipe to serve as pressure taps. Ten one-half inch holes were drilled on the opposite side of the column to serve as gas injection holes.

The false bottom was a cone that fitted on the bottom of the column, and the diameter of the hole at the bottom of this cone determined the rate of flow of solids. The cone was a thin aluminum plate, and was analogous to the slide valve used in some commercial operations. It was believed that a slide valve would create a dead zone in this small-scale equipment, and that a cone would allow more uniform downward movement of the solids. Three types of injection tubes made of 1/4-inch copper tubing were used. Type number one was a tube extending from the wall to the center of the column. The tube was bent ninety degrees so that the outlet was pointed up along the centerline. Type number two was a tube extending from one wall to the opposite wall. This tube had four 1/16-inch diameter holes drilled in it. These holes were evenly spaced on one side along the length of the injection tube. Type number three was a cross. This cross was two tubes of type number two connected at the center, with only one gas inlet.

Pressures were read on water-filled manometers. A pipe cleaner was inserted in the pressure tap line at the standpipe end to keep the pressure line free of solids.

Rotameters were used to meter the gas into the column. Calibration data on these rotameters are found in Appendix C.

On the runs using the conical false bottom a five-gallon can was fastened at the bottom of the column. The can received the solids and prevented the fluidizing medium escaping from the bottom of the column.

CHAPTER IV

EXPERIMENTAL PROCEDURE

The tests were divided into three groups. In group one a used microsphere - cracking catalyst was employed, while in group two a new one was used. In group three two series of runs were made: one series in which the used catalyst was employed and a second using the new catalyst. The new catalyst was obtained from American Cynamide Company, and the used catalyst was obtained from Cities Service Oil Company. The analysis of both of these catalysts was made by the American Cynamide Company. The analysis of the two catalysts is found in Appendix C.

The test runs are lettered from A to O. Runs A through C were made with the new catalyst, and Runs D through F were made with the used catalyst. Runs G through O were made using both catalysts in the same manner as Run F. One set of operating conditions will be given as an example.

Runs G through O were made in the same manner as Run E, but the solid flow rate was changed. Both new and used solids were used in Runs G through O, each run being labeled as either new or used catalyst.

It was thought that the bottom of the column should be closed and some data obtained in the confined bed. These runs are labeled A. Then the cone was placed on the bottom of the column, a flow rate established, and data obtained. These runs are labeled B. In Runs A the minimum rate of fluidizing gas for fluidization was found. In Run C this minimum fluidizing rate was added to a column with no catalyst, and catalyst in weighted amounts was added to the column. Pressure readings were recorded after each addition.

In the A runs the catalyst was added to the column to a height of forty-nine inches from the bottom. Air was introduced in different amounts using the three types of injection points. Pressure drops were measured at various points on the column.

In Runs B catalyst was added to the column and a rate-of-flow of solids from the bottom of the column was established. Air was introduced in different amounts using the three types of injection points. Pressure drops were measured at various points on the column. Catalyst was added manually to maintain a fluidized height of forty-nine inches in the bed.

In some of the runs the pressure-drop curve was established by increasing the flow rate past the minimum fluidization rate and then, without doing anything to the system, the pressure drop was observed by slowly decreasing the air flow. Runs 3A and 1D are examples of this procedure.

Runs 5A-1 and 5A-2 were made to check the addition of air, using two injection lines. The top part of the bed was fluidized using injection location F. A minimum gas rate was found which was maintained while air was added at the bottom of the column, using injection point A. A minimum gas rate was established at this point. A comparison of this run and a run using only injection point A was made.

In Runs G through O, the catalyst flow rate was changed by changing the diameter of the hole in the bottom of the cone.

There was some question as to the validity of the pressure point taps used. A pressure traverse was made across a diameter of the column to establish that the pressure measured at the wall of the column was representative.

CHAPTER V

DISCUSSION OF RESULTS

Because of the quantity of data, the results are divided into three main groups. Group one consists of Runs A and B; group two consists of Runs D and E; and group three consists of Runs G through O. The data are summarized in Table I. For details of conditions of each run, see Chapter IV.

The three types of injection points used made very little difference in the amount of air required for fluidizing the microsphere-cracking catalyst. An average air velocity (expressed as feet per hour) of twenty-five feet per hour, plus or minus one foot per hour, was needed to fluidize the bed with zero net downward particle motion. As the net downward motion of the catalyst increased, the amount of gas needed for fluidization increased. This is shown in Figure 10.

It took more air to fluidize the used catalyst than it did the new catalyst. The average particle size was the same, but the used catalyst had a much higher bulk density. The pressure drop across the used catalyst was also greater.

Runs 3A (Figure 13) points out an interesting relation in the gas rates needed in a fluid bed. Two curves are

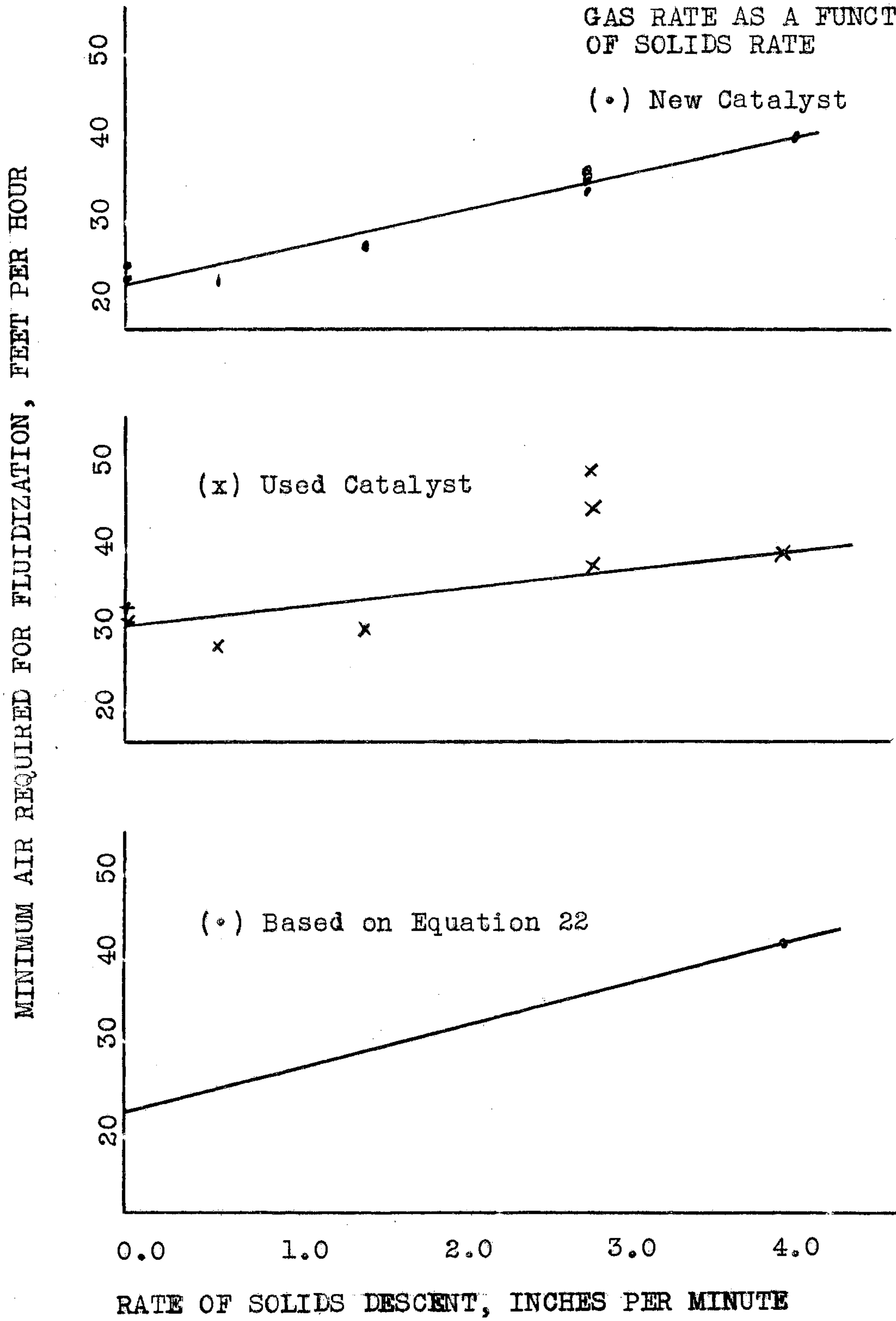
TABLE I

SUMMARY OF EXPERIMENTS

Run	Type Catalyst	Net Catalyst Velocity in./min.	Minimum Air Required ft./hr.	Figure Number
7A	New M. S.	0.0	26±0.2	16
8A	New M. S.	0.0	25±0.5	17
9A	New M. S.	0.0	24±0.5	18
2B	New M. S.	3.0	37±0.2	21
3B	New M. S.	3.0	35.5	22
4B	New M. S.	3.0	36±0.2	23
1D	Used M. S.	0.0	32.0	25
2D	Used M. S.	0.0	37.0	27
4D	Used M. S.	0.0	33.0	29
IE	Used M. S.	3.0	40	30
2E	Used M. S.	3.0	44	31
3E	Used M. S.	3.0	50	32
1G	Used M. S.	0.5	26.5±0.5	33
1H	Used M. S.	1.5	31.5±0.5	34
1I	New M. S.	1.5	27.8	35
1J	New M. S.	0.75	24	36
1K	New M. S.	0.75	25.5	37
1L	Used M. S.	4.0	41.0	38
1M	Used M. S.	4.0	40.1	39
1N	New M. S.	4.0	40.2	40
1O	New M. S.	4.0	40.1	41

FIGURE 10

GAS RATE AS A FUNCTION OF SOLIDS RATE



plotted--one with an increasing gas velocity and the other with a decreasing gas velocity. This data shows that it takes less gas to keep a bed fluidized than it does to fluidize a static bed.

A simple experiment was devised to determine if the pressure readings were the same along the axis of the column as they were at the wall of the column. It was found that the pressure was the same at the wall and at the center of the column at a given height.

In runs 5A-1 and 5A-2 it was found that by placing two injection points in the column in different locations no less gas was required to fluidize the total bed. In standpipes when the solids are moving very rapidly the only reason for having multiple points is to keep agglomerates from forming. Multiple points should not be sought where minimum use of fluidizing gas is required.

A correlation was found to exist between the amount of air needed for fluidization and the terminal settling velocity of a single sphere. Equation (14) shows this relation.

$$V_n = 2/3\ u_t + V_p \qquad (14)$$

The derivation of this equation is found in Appendix D.

CHAPTER VI

SUMMARY AND CONCLUSIONS

A correlation between the terminal settling velocity and minimum velocity required for fluidization has been found for a microsphere-cracking catalyst. This relation is as follows:

$$V_n = 2/3\ u_T + V_P \qquad (14)$$

The type of injection system made very little difference in the amount of air required to fluidize a given bed of catalyst. The three types of injection systems included a point, a tube, and a cross.

This experimental work shows that multiple injection points at different heights require more air to fluidize a given volume of catalyst.

Less gas is required to keep a bed in the fluidized state than to reach a fluidized state from a static condition. There seems to be a third force, the effect of which is to retain the bed in a compacted state. An experimental program should be carried out to see what this force is.

The experiments which form the basis for this thesis were done with a microsphere catalyst, which, from a theoretical standpoint, should give the most ideal results. There are several fluid catalysts that are inherently hard to fluidize. An experimental program should be carried out to see if the equation derived in this work could be used when other solids were fluidized.

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APPENDICES

APPENDIX A

DEFINITIONS AND NOMENCLATURE

1. A "fixed bed" is a body of motionless solid particles supported by direct contact with each other and the retaining walls.

2. A "moving bed" is a similar body in which the particles remain in direct contact and are substantially fixed in position with respect to each other, but move with respect to the retaining walls.

3. A "fluidized mass" of solid particles is one which exhibits the mobility and hydrostatic pressure characteristic of a fluid. This condition may be achieved through suspending the particles by means of a stream of gas or liquid rising past the particles.

4. A "fluidized bed" is a mass of solid particles which exhibits the liquid-like characteristics of mobility, hydrostatic pressure, and an observable upper free surface or boundary zone across which a marked change in concentration of particles occurs. (In a fluidized bed, the random motion of the particles increase with increasing velocity of the supporting medium.)

4a. "Particulate fluidization" of a bed refers to a condition in which the particles are individually and uniformly dispersed. (Particulate fluidization is commonly observed in beds fluidized by a current of liquid. The term "tectering" as used in the ore-dressing industry refers to a relatively high-density suspension of this type.) In contrast, coexistence of dense and dilute suspensions (bubbles) within a fluidized bed is termed "aggregative fluidization" (aggregative fluidization is commonly observed in beds fluidized by a current of gas).

4b. A "quiescent fluidized bed" is a dense fluidized bed which exhibits little or no mixing of the solid particles. (Such a bed is analogous to a body of liquid at rest, having a well-defined upper free surface.)

4c. A "turbulent fluidized bed" is a fluidized bed in which mixing of the mass of solids takes place. (The degree of turbulence, increasing from the lower limit of quiescent-bed conditions to violent mixing, depends upon the dynamics of the system. The passage of bubbles through the bed may give rise to such turbulence and mixing. While such a bed may operate at a gas velocity below the free-falling velocity for the bulk of the solid particles, it can also be maintained at a velocity materially above the free-falling velocity if a continuous feed of solids is supplied to the bed. The boundary zone or interface at the free upper surface of a turbulent fluidized bed is generally diffuse, as in the surface of a boiling liquid.)

5. A "dispersed suspension" is a mass of solid particles or aggregates suspended in a current of liquid of gas rising past the particles, which differs from a fluidized

bed in that an upper level or interface is not formed under conditions of continuous solids entrainment and uniform superficial velocity. (This is usually observed under conditions of low solids feed rate. Thus, in general, a dispersed suspension is analogous to a vapor, whereas a fluidized bed is analogous to a liquid. One example of this condition is observed in a pneumatic transport. In a vessel containing a fluidized bed a dilute suspension of entrained particles above the bed also is such a dispersed suspension and is frequently referred to as the "dispersed phase" while the bed itself is referred to as the "dense phase".)

6. "Channeling" is the establishment of flow paths in a bed of solid particles through which a disproportionate quantity of the introduced liquid passes.

7. "Slugging" is a condition in which pockets of bubbles of the supporting fluid grow to the diameter of the containing vessel, and the mass of particles trapped between adjacent pockets moves upward in a piston fashion. (This condition is usually limited to a vessels of high length-to diameter ratio.)

8. The term "dense phase" is used to denote a high ratio of solids to gas, and the term "dilute phase" is used to denote a low ratio of solids to gas in a fluidized system.

9. "Aeration" is the act of forcing gas into the spaces between the solid particles.

10. "Deaeration" is the act of releasing the gas from the spaces found between solid particles.

Nomenclature:

A	=	Area of bed
K	=	Constant
Kdp	=	Pressure drop
K	=	Pressure drop
L and L_f	=	Thickness of bed or height of bed
L_o	=	Height of an equivalent bed without fluidization
L_1	=	Length of flow path
N_{Fr}	=	Froude number (dimensionless)
N_{Re}	=	Reynolds number
V_P	=	Net velocity of particle with respect to walls
V	=	Volume of particle
Vn	=	Velocity required for fluidization
V^g	=	Volume of gas per unit time in the discontinuous phase
V^v	=	Volume of gas per unit time in the continuous phase
dp	=	Diameter of particle
g	=	Gravitational constant
g_c	=	Conversion gravitational constant
k	=	Constant
u_o	=	Segregation rate
u_t	=	Terminal gravitational setting velocity
v	=	Velocity
v_p	=	Velocity of particle
ϵ	=	Porosity of bed
$\epsilon 3, \epsilon 2, \epsilon 1$	=	Porosity in different sections of bed
F_f	=	Modified friction factor

P	=	Pressure drop
$-\Delta P_f$	=	Pressure drop required for fluidizing
Δp^{ke}	=	Total pressure drop due to kinetic energy loss
Δp^{mf}	=	Total pressure drop at incipient fluidization
ρ and ρ_f, ρg	=	Density of fluidizing medium (fluid)
s	=	Density of solid
μ	=	Viscosity of fluid
λ	=	Shape factor
G	=	Mass velocity of fluid

APPENDIX B

APPARATUS DETAILS

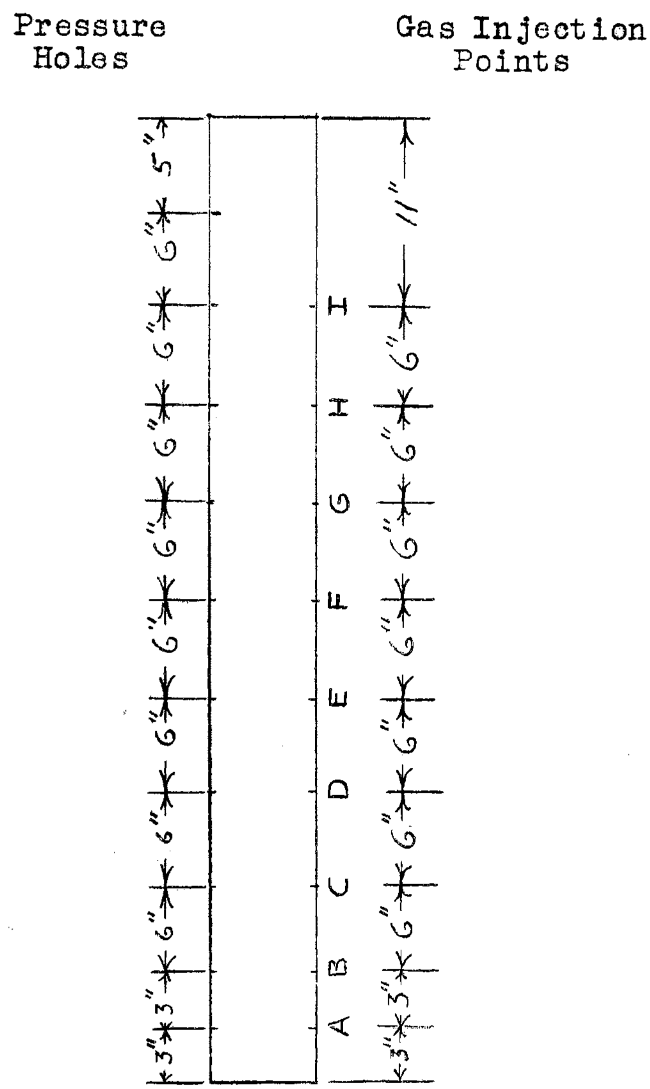
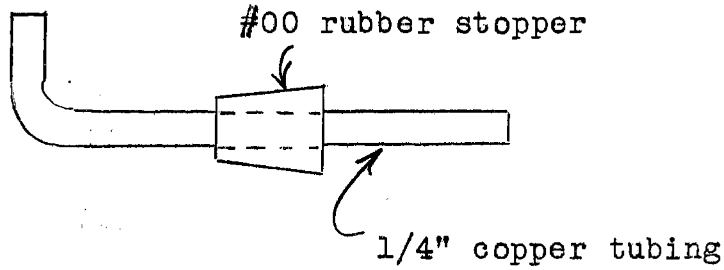


FIGURE 11. COLUMN DETAILS

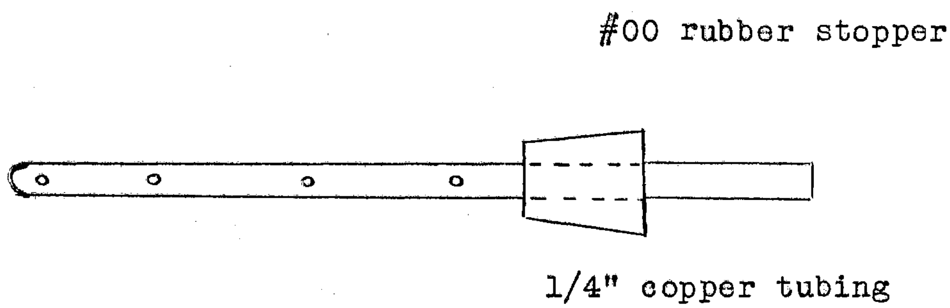
Injection Point Details

Type Number One



side view

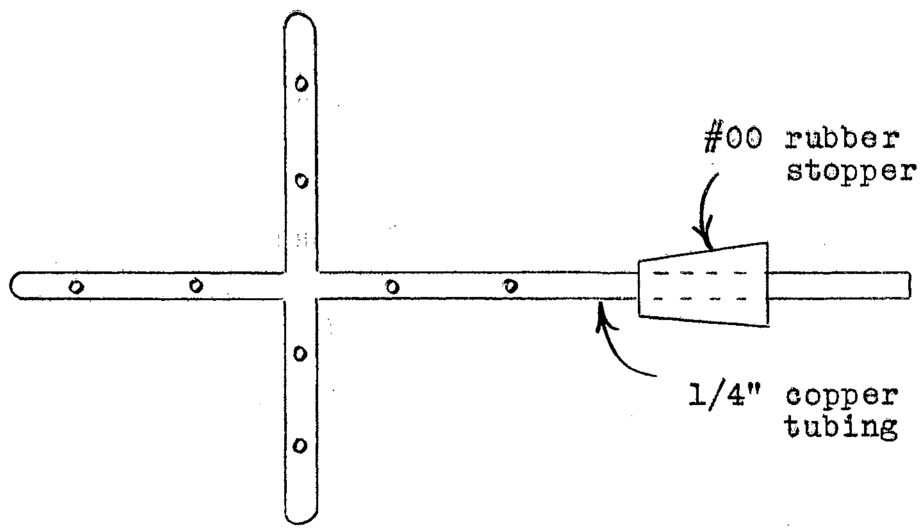
Type Number Two



top view

FIGURE 12. GAS INJECTION DETAILS

Type Number Three



top view

Cone Details

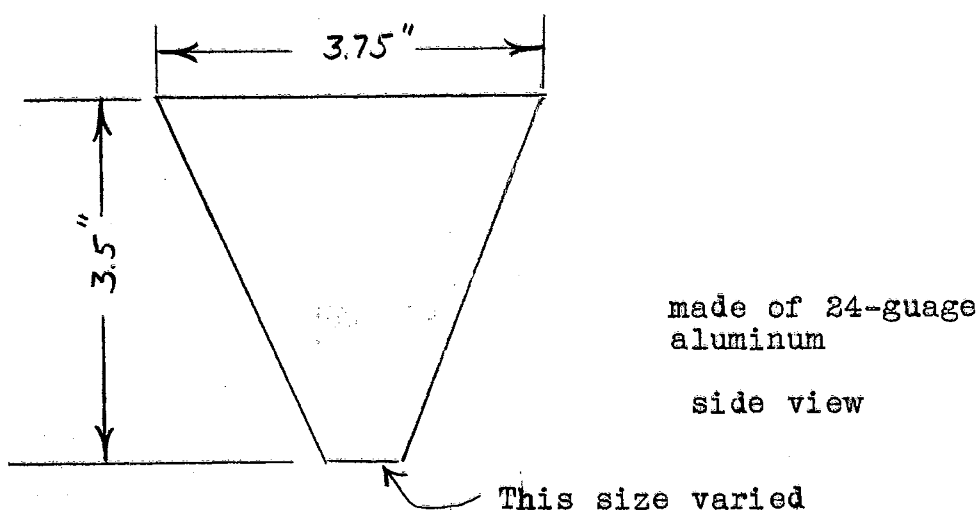


FIGURE 13. INJECTION DETAILS AND CONE DETAILS

APPENDIX C

DATA

Inspection data on cracking catalyst--Sample FW 1778, American Cyanamide Company (new microsphere)

Grade 60/70 (Sample No. FW 1778)

Chemical Analysis (Ignited bases)	
% Al_2O_3	13.9
% SO_4	0.42
% Na_2O	0.05
% Fe	0.03

Physical Properties

Particle Size	Wt. %
less than 150 microns	99
100 microns	87
80 microns	70
74 microns	65
40 microns	19
30 microns	10
20 microns	3
10 microns	1
average particle size (microns)	62

The test methods are in the Cyanamide Manual of Test Methods.

Structure

Surface area	575 m^2/g
Pore volume	0.83 cc/g
Apparent bulk density	0.41 g/cc

Catalytic activity

Volume basis	87
Weight basis	105

Inspection data on cracking catalyst--Sample from Cities Service Oil Company (used microsphere)

Chemical Analysis (Dry basis % by weight)	
Al_2O_3	20.0
Fe	0.22
Na_2O	0.13
C	0.5

Physical Properties

Particle Size	Wt. %
less than 150 microns	99
100 microns	93
90 microns	89
80 microns	84
74 microns	81
70 microns	73
60 microns	43
50 microns	23
40 microns	8
30 microns	0
20 microns	0
10 microns	0
average particle size (microns)	62

Structure

Surface area	126 m^2/g
Pore volume	0.45 cc/g
Apparent bulk density	0.70 g/cc

Catalytic activity

Volume basis	52
Weight basis	38

Validity of Pressure Taps

Location of pressure tap--Point 3	Pressure indicated, MM of HOH
Pressure Tap at wall of column	370
Pressure Tap 1/2 inch from edge	370
Pressure Tap 1 inch from edge	370
Pressure Tap 1 1/2 inch from edge	370
Pressure Tap at center of column	370

Rotameter Calibration (cu. ft. at 745 mm. Hg and 78° F.)

Rotameter #1

Rotameter setting	Meter settings cu. ft./min. Before	- After	Time (sec.)
1.05	0	0.089	120
2.0	0	0.122	60
2.9	0	0.182	60
3.8	0	0.238	60
5.25	0	0.2	34.1
6.25	0	0.304	41.5
8.7	0	0.3	29.9

Rotameter #2

Rotameter setting	Meter settings cu. ft./min. Before	- After	Time (sec.)
1.1	0	0.05	72
2.3	0	0.1	74.3
3.0	0	0.1	41.5
3.8	0	0.2	46.5
5.05	0	0.3	54.1
6.2	0	0.3	43.8
7.7	0	0.4	48.5
9.5	0	0.5	51.5

Rotameter #3

Rotameter setting	Meter settings cu. ft./min. Before	- After	Time (sec.)
2	0	0.02	50.3
3	0	0.26	40.4
4.2	0	0.04	39.5
5.6	0	0.1	64.3
6.65	0	0.1	50.3
7.75	0	0.1	41.7
9.1	0	0.1	32.9
10.3	0	0.2	56.4
11.7	0	0.2	49.4
13	0	0.2	41.8
14.7	0	0.2	36.1

Rotameter #4

Rotameter setting	Meter settings cu. ft./min. Before	After	Time (sec.)
1.5	0	0.02	42.3
3.8	0	0.03	37.5
5.65	0	0.04	37.2
6.95	0	0.1	79.2
6.95	0	0.1	80
8.8	0	0.15	101.4
11.85	0	0.1	51.3
14.4	0	0.1	42.3
17.65	0	0.1	34.7
20.0	0	0.15	46.3
22.9	0	0.2	54.1
24.8	0	0.2	51.0

Rotameter #5

Rotameter setting	Meter settings cu. ft./min. Before	After	Time (sec.)
1.0	0	0.02	51.1
3.0	0	0.03	42.5
6.0	0	0.05	40.5
9.0	0	0.10	55.2
12.0	0	0.15	61.0
15.0	0	0.15	48.9
18.0	0	0.20	54.7
22.0	0	0.20	43.3
24.9	0	0.20	38.0

Data for Runs B and E

Catalyst flow rate data (new catalyst)

Time (min.)	Height of catalyst from top of column (in.)
0	11
1	14
0	11
1	13.8
0	11
1	14.2

Catalyst density, bulk (new catalyst)

977 gms. gross
-553 gms. tare or 424^{g}/100 cc. or 0.42 g/cc.
424 gms. net

Catalyst flow rate data (used catalyst)

Time (min.)	Height from top of column (in.)
0	10
1	13

Data

Run number. 1A

Data. 3/27/56

Type injection point. . . . . .Number One

Location injection point. . . . . .Point A

Location pressure taps. . . . . .ΔP_1 at 1

ΔP_2 at 2

ΔP_3 at 3

ΔP_4 at 4

ΔP_5 at 5

Height of bed from bottom of column, inches . . .49

Rotameter used. .Number One

Type catalyst . . . . .New M. S.

Rotameter setting	ΔP_1	ΔP_2	ΔP_3	ΔP_4	ΔP_5	Height of bed, (in.)
	(millimeters of water)					
1.80	360	380	370	320	280	58 1/4
1.60	370	385	380	320	280	56 1/2
1.10	360	365	365	315	275	54 3/4
0.90	360	360	360	310	270	53

Data

Run number. 2A

Data. 3/28/56

Type injection point. . . . . .Number One

Location injection point. . . . . .Point A

Location pressure taps. . . . . .ΔP_1 at 6

ΔP_2 at 7

ΔP_3 at 8

ΔP_4 at 9

ΔP_5 at 10

Height of bed from bottom of column, inches . . .49

Rotameter used. . . . . .Number One

Type catalyst . . . . .New M. S.

Rotameter setting	ΔP_1	ΔP_2 (millimeters of water)	ΔP_3	ΔP_4	ΔP_5	Height of bed (in.)
1.60	217	162	108	50	4	54 3/4
1.80	210	160	115	60	10	55 1/2
1.10	202	143	98	43	2	52 1/2

Data

Run number. 3A

Data. 3/28/56

Type injection point. . . . . .Number One

Location injection point. . . . . .Point A

Location pressure taps. . . . . .ΔP_1 at 1

ΔP_2 at 2

ΔP_3 at 3

ΔP_4 at 4

ΔP_5 at 5

Height of bed from bottom of column, inches . . .49

Rotameter used. .Number Four

Type catalyst . . . . .New M. S.

Rotameter setting	ΔP_1 (millimeters of water)	ΔP_2	ΔP_3	ΔP_4	ΔP_5	Height of bed (in.)
0.5	430	420	355	270	240	49
0.75	450	440	375	295	255	49
1.25	510	505	425	335	290	49
2.6	350	365	360	305	270	53
3.65	350	365	360	310	270	54
5.15	360	380	370	310	275	55
7.0	365	385	375	315	280	56
10.2	375	390	380	315	280	56 1/4

The velocity will be decreased slowly especially in the range of the "break".

Rotameter setting	ΔP_1 (millimeters of water)	ΔP_2	ΔP_3	ΔP_4	ΔP_5	Height of bed (in.)
6.5	365	384	372	314	277	56
5.15	360	376	375	313	275	55 3/4
3.55	352	367	359	315	272	54 1/4
3.55	352	366	363	310	272	54 1/4

Run number 3A (continued)

Rotameter setting	ΔP_1	ΔP_2	ΔP_3	ΔP_4	ΔP_5	Height of bed (in.)
	(millimeters of water)					
2.85	345	360	360	310	270	53 1/2
2.5	350	364	358	308	266	53 1/2
2.3	346	363	355	310	270	53 1/4
2.05	346	357	355	306	266	53
1.75	335	352	356	307	265	52 1/2
1.30	320	340	336	305	267	52 1/4
1.0	326	344	340	308	265	52
0.75	356	375	355	286	250	51 1/2
0.55	347	367	340	270	240	51 1/2
0.25	312	325	315	253	222	51 1/4

Turned air off -- let settle "naturally" -- no external movement to cause settling.

Rotameter setting	ΔP_1	ΔP_2	ΔP_3	ΔP_4	ΔP_5	Height of bed (in.)
	(millimeters of water)					
0.35	380	370	312	248	218	51 1/4
0.65	415	405	340	270	240	51 1/4
0.85	440	430	362	290	255	51 1/4
1.20	468	455	385	310	270	51 1/4
1.45	486	477	404	325	280	51 1/4
1.75	514	505	425	340	300	51 1/4
2.0	360	375	358	307	268	52 1/4

Turned air off -- settled to a height of 49"

Rotameter setting	ΔP_1	ΔP_2	ΔP_3	ΔP_4	ΔP_5	Height of bed (in.)
	(millimeters of water)					
0.5	430	425	360	295	256	49
0.9	484	460	410	330	285	49
1.6	565	550	462	380	325	49

Data

Run number. 4A

Date. 3/29/56

Type injection point. . . . . Number One

Location injection point. . . . . Point A

Location pressure taps. . . . . ΔP_1 at 10
ΔP_2 at 9
ΔP_3 at 8
ΔP_4 at 7
ΔP_5 at 6

Height of bed from bottom of column, inches . . . 49

Rotameter used. Number Four

Type catalyst . . . . New M. S.

Rotameter setting	ΔP_1 (millimeters of water)	ΔP_2	ΔP_3	ΔP_4	ΔP_5	Height of bed (in.)
0.5	0	16	55	125	195	49
1.15	0	18	60	145	225	49
1.70	0	41	80	145	205	-

Ran rate up and turned down rate gradually.

Rotameter setting	ΔP_1 (millimeters of water)	ΔP_2	ΔP_3	ΔP_4	ΔP_5	Height of bed (in.)
10.0	10	65	95	170	225	56
7.6	12	70	95	167	222	56
5.45	15	70	95	165	220	55 3/4
2.8	12	68	92	160	210	55 1/4
1.9	0	55	80	150	210	53
1.45	0	50	80	150	207	52 3/4
1.05	0	45	76	150	205	52
0.60	0	40	72	140	195	51 1/2

Cut off air -- let bed settle "naturally".

Run number 4A (continued)

Rotameter setting	ΔP_1 (millimeters of water)	ΔP_2	ΔP_3	ΔP_4	ΔP_5	Height of bed (in.)
0.5	0	18	55	120	180	50 1/4
0.7	0	20	58	130	195	50 1/4
0.95	0	24	62	140	207	50 1/4
1.25	0	25	65	148	220	50 1/4
1.65	0	25	70	158	240	50 1/4
2.05	0	25	74	165	240	50 1/4
2.7	0	47	83	150	210	54 1/4
5.5	0	64	90	160	216	56 1/4

Cut off air -- settled to a height of 49"

Rotameter setting	ΔP_1 (millimeters of water)	ΔP_2	ΔP_3	ΔP_4	ΔP_5	Height of bed (in.)
0.55	0	17	52	123	190	49
1.55	0	15	60	150	240	49
2.20	0	50	78	155	210	52
5.10	0	55	80	160	210	54 3/4

Data

Run number. 5A-1
5A-2

Date. 3/29/56

Type injection points . . . . .Number One

Location injection points . . . . .Point A
Point F

Location pressure taps.	5A-1	5A-2
	ΔP_1 at 10	ΔP_1 at 1
	ΔP_2 at 9	ΔP_2 at 3
	ΔP_3 at 8	ΔP_3 at 6
	ΔP_4 at 7	ΔP_4 at 7
	ΔP_5 at 6	ΔP_5 at 9

Height of bed from bottom of column, inches . . .49

Rotameter used. . . . . 5A-1 Number Three
5A-2 Number Four

Type catalyst . . . . .New M. S.

Run 5A-1
(only injection point F was used)

Rotameter setting	ΔP_1	ΔP_2	ΔP_3	ΔP_4	ΔP_5	Height of bed (in.)
	(millimeters of water)					
1.4	0	11	41	65	100	49
1.8	0	15	53	95	129	49
2.18	0	17	77	142	193	49
2.50	0	20	70	105	112	49 1/2
3.0	0	20	71	108	112	49 3/4

The pressure taps were changed over to the ones indicated for test 5A-2.
ΔP_4 was not changed, therefore, the reading should be approximately equal.

2.5	56	72	106	108	18	49 3/4

Run number 5A-1 and 5A-2 (continued)

Rotameter number three was placed at reading of 2.5 throughout run 5A-2.

Run 5A-2

Both injection points are used: A and F

Rotameter setting	ΔP_1	ΔP_2	ΔP_3	ΔP_4	ΔP_5	Height of bed (in.)
	(millimeters of water)					
0.3	374	327	185	123	22	50
0.5	386	338	185	125	22	50 1/4
0.7	407	355	185	125	22	50 1/4
1.0	430	368	188	125	22	50 1/4
1.1	437	378	188	125	22	50 1/4
1.2	445	382	188	125	22	50 1/2
1.4	461	395	188	128	23	50 1/2
1.55	473	402	190	128	23	50 3/4
1.8	488	413	188	128	23	50 3/4
2.0	500	420	188	128	23	51
2.15	332	350	212	151	50	53
2.35	332	350	213	152	50	54
2.70	336	355	214	156	58	54 1/2
3.5	340	362	215	157	59	55
5.3	350	367	217	160	60	55 1/4
(Placed setting back to 2.5 and checked)						
2.15	332	350	212	151	50	-
(Now cut off injection point at F.)						
2.15	322	345	215	152	49	-

Data

Run number. 6A

Date. 3/29/56

Type injection point. . . . . .Number Two

Location injection point. . . . . .Point A

Location pressure taps. . . . . ΔP_1 at 1

ΔP_2 at 3

ΔP_3 at 6

ΔP_4 at 7

ΔP_5 at 9

Height of bed from bottom of column, inches . . .49

Rotameter used. . . . . .Number Four

Type catalyst .New M. S.

Rotameter setting	ΔP_1 (millimeters of water)	ΔP_2	ΔP_3	ΔP_4	ΔP_5	Height of bed (in.)
0.2	388	314	173	113	18	49
0.45	421	343	186	122	18	49
0.6	436	353	195	127	18	49
0.8	465	372	204	133	19	49
1.05	488	395	218	140	19	49
1.3	520	420	228	148	19	49 1/8
1.5	540	435	236	152	19	49 1/8
1.6	544	436	239	153	19	49 1/8
1.8	555	444	240	156	19	49 1/8
2.0	570	456	248	160	19	49 1/8
2.3	580	-	-	-	-	-
2.5	548	411	223	160	42	52 1/2
2.75	390	377	220	160	62	55
3.4	395	378	221	161	66	56
4.6	408	381	225	167	70	57
6.1	413	385	226	168	74	57 1/2

Data

Run number. 7A

Date. 4/1/56

Type injection point. . . . . .Number Three

Location injection point. . . . . .Point A

Location pressure taps. . . . . .ΔP_1 at 1

ΔP_2 at 3

ΔP_3 at 6

ΔP_4 at 7

ΔP_5 at 9

Height of bed from bottom of column, inches . . .49

Rotameter used. . . . . .Number Four

Type catalyst .New M. S.

Rotameter setting	ΔP_1 (millimeters of water)	ΔP_2	ΔP_3	ΔP_4	ΔP_5	Height of bed (in.)
0.3	455	382	205	138	15	49
1.15	567	470	245	160	15	49
1.35	585	486	258	170	15	49
1.55	595	507	268	178	15	49
1.75	410	375	225	167	56	52
2.3	414	380	230	168	57	53 1/2
2.8	416	385	230	170	58	54
3.8	418	389	235	170	60	54 3/4

Remarks: Bottom of column completely closed.

Data

Run number. 8A

Date. 4/1/56

Type injection point. . . . . Number Two

Location injection point. . . . . Point A

Location pressure taps. . . . . ΔP_1 at 1
ΔP_2 at 3
ΔP_3 at 6
ΔP_4 at 7
ΔP_5 at 9

Height of settled bed from bottom of column, inches 49

Rotameter used. . . . . Number Four

Type catalyst . . . . New M. S.

Rotameter setting	ΔP_1	ΔP_2 (millimeters of water)	ΔP_3	ΔP_4	ΔP_5	Height of bed (in.)
0.5	473	410	226	150	10	49
0.7	520	444	243	160	11	49
1.15	572	490	265	177	12	49
1.75	384	372	220	165	53	53
2.5	390	372	225	165	55	54
3.9	395	380	230	170	60	55

Data

Run number. 9A

Date. 4/1/56

Type injection point. . . . . .Number One

Location injection point. . . . . .Point A

Location pressure taps. . . . . .ΔP_1 at 1

ΔP_2 at 3

ΔP_3 at 6

ΔP_4 at 7

ΔP_5 at 9

Height of settled bed from bottom of column, inches 49

Rotameter used. . . . . .Number Four

Type catalyst . . . . .New M. S.

Rotameter setting	ΔP_1 (millimeters of water)	ΔP_2	ΔP_3	ΔP_4	ΔP_5	Height of bed (in.)
0.4	455	392	212	145	10	49
0.7	510	438	235	160	11	49
1.0	545	460	245	165	12	49
1.5	367	370	230	170	50	53
1.8	370	375	235	172	54	53 1/2
3.4	373	380	230	175	58	54 1/2

Data

Run number. 1B

Date. 4/13/56

Type injection point. . . . . .Number One

Location injection point. . . . . .Point A

Location pressure taps. . . . . .ΔP_1 at 1

ΔP_2 at 3

ΔP_3 at 6

ΔP_4 at 7

ΔP_5 at 9

Height of bed from bottom of column, inches . . .49

Rotameter used. .Number Four

Rate catalyst flow in column. . . . . .3 inches per minute

Type catalyst . . . . .New M. S.

Rotameter setting	ΔP_1	ΔP_2	ΔP_3	ΔP_4	ΔP_5
	(millimeters of water)				
0.9	256	316	156	92	2
1.50	360	315	145	85	5
0.2	355	316	184	115	-
0.5	367	335	168	115	15
0.7	372	333	170	108	-
2.0	370	340	172	110	20
0.1	365	335	176	120	20
0.4	370	340	170	130	22

Data

Run number. 2B

Date. 4/13/56

Type injection point. . . . . .Number Two

Location injection point. . . . . .Point A

Location pressure taps. . . . . .ΔP_1 at 1

ΔP_2 at 3

ΔP_3 at 6

ΔP_4 at 7

ΔP_5 at 9

Height of bed from bottom of column, inches . . .49

Rotameter used. .Number Four

Rate catalyst flow in column. . . . . .3 inches per minute

Type catalyst . . . . .New M. S.

Rotameter setting	ΔP_1	ΔP_2	ΔP_3	ΔP_4	ΔP_5
	(millimeters of water)				
0.1	391	330	166	115	12
0.3	407	345	175	65	16
0.6	410	345	174	65	17
0.8	405	335	170	110	18
1.0	395	330	164	110	14
1.4	403	332	165	112	17
1.8	400	327	168	111	18
2.3	410	335	175	120	21
4.5	413	338	178	121	22

Data

Run number. 3B

Date. 4/13/56

Type injection point. . . . . .Number Three

Location injection point. . . . . .Point A

Location pressure taps. . . . . .ΔP_1 at 1
ΔP_2 at 3
ΔP_3 at 6
ΔP_4 at 7
ΔP_5 at 9

Height of bed from bottom of column, inches . . .49

Rotameter used. .Number Four

Rate catalyst flow in column. . . . . .3 inches per minute

Type catalyst . . . . .New M. S.

Rotameter setting	ΔP_1	ΔP_2	ΔP_3	ΔP_4	ΔP_5
	(millimeters of water)				
0.20	410	342	174	65	18
0.30	412	345	176	67	18
0.40	405	336	172	62	18
0.60	392	332	165	63	16
0.95	396	336	170	66	17
1.3	400	340	176	67	18
2.0	410	345	178	70	19

Data

Run number. 4B

Date. 4/13/56

Type injection point. . . . . .Number One

Location injection point. . . . . .Point A

Location pressure taps. . . . . .ΔP_1 at 1

ΔP_2 at 3

ΔP_3 at 6

ΔP_4 at 7

ΔP_5 at 9

Height of bed from bottom of column, inches . . .49

Rotameter used. . . . . .Number Four

Rate catalyst flow in column. . . . . .3 inches per minute

Type catalyst .New M. S.

Rotameter setting	ΔP_1	ΔP_2	ΔP_3	ΔP_4	ΔP_5
	(millimeters of water)				
0.15	365	336	184	130	20
0.25	375	340	186	134	20
0.45	385	341	186	135	20
0.65	360	334	172	160	18
1.0	365	336	173	118	19
1.3	375	338	175	112	10
1.6	376	340	176	108	8
2.7	380	341	178	108	8

Data

Run number. 5B-1
5B-2

Date. 4/19/56

Type injection points . . . . .Number One

Location injection points . . . . .Point A
Point F

Location pressure taps. . . . . .ΔP_1 at 1

ΔP_2 at 3

ΔP_3 at 6

ΔP_4 at 7

ΔP_5 at 9

Height of bed from bottom of column, inches . . .49

Rotameter used. . . . . 5B-1 Number Three
5B-2 Number Four

Type catalyst . . . . .New M. S.

Run 5B-1

(Only injection point F was used)

Rotameter setting	ΔP_1 (millimeters of water)	ΔP_2	ΔP_3	ΔP_4	ΔP_5
0.3	160	172	115	80	0
0.45	180	220	145	100	0
0.75	185	250	184	130	0
1.20	150	235	120	95	0
1.95	200	195	155	120	0

Rotameter number 3 was set at a reading of 1.2 and left at this point throughout run 5B-2

Run number 5B-1 and 5B-2 (continued)

Run 5B-2

Both injection points are used: A and F

Rotameter setting	ΔP_1	ΔP_2	ΔP_3 (millimeters of water)	ΔP_4	ΔP_5
0.2	374	345	180	120	0
0.4	390	350	185	110	0
0.7	370	340	175	120	0
1.0	385	342	180	125	0
1.5	390	347	162	102	0
0.9	375	340	180	-	0
0.6	376	337	160	105	0
0.3	383	350	186	130	20

Rotameter Number Four at minimum (0.6)

Rotameter setting	ΔP_1	ΔP_2	ΔP_3 (millimeters of water)	ΔP_4	ΔP_5
0.6	376	337	160	105	0

Cut off Rotameter Number Three

Rotameter setting	ΔP_1	ΔP_2	ΔP_3 (millimeters of water)	ΔP_4	ΔP_5
	376	337	160	105	0

Data

Run number. 1C

Date. 4/14/56

Type injection point. . . . . .Number One

Location injection point. . . . . .Point A

Location pressure taps. . . . .ΔP_1 at 1
ΔP_2 at 3
ΔP_3 at 6
ΔP_4 at 7
ΔP_5 at 9

Rotameter used. . . . . .Number Four

Rotameter was set at 1.5 (determined in run 9A) with no catalyst in tube. Catalyst is added in 200 grams increments.

Type catalyst . . . . .New M. S.

Rotameter setting . . . .(1.5)

Weight of catalyst in tube, grams	Height of catalyst in tube, from bottom, inches	ΔP_1 (millimeters of water)	ΔP_2	ΔP_3	ΔP_4	ΔP_5
200	-	0	0	0	0	0
400	-	2	0	0	0	0
600	9 1/2	14	0	0	0	0
800	12 1/4	38	5	0	0	0
1000	15 1/4	66	32	0	0	0
1200	18 1/4	95	60	0	0	0
1400	21 1/2	123	80	0	0	0
1600	25	153	120	0	0	0
1800	28 1/4	183	148	0	0	0
2000	31 3/4	217	181	13	0	0
2200	35 1/4	245	210	46	0	0
2400	38 1/4	285	241	80	24	0
2600	42	310	274	110	52	0

Run number 10 (continued)

Weight of catalyst in tube, grams	Height of catalyst in tube, from bottom, inches	ΔP_1	ΔP_2	ΔP_3	ΔP_4	ΔP_5
		(millimeters of water)				
2800	46	330	307	142	78	0
3000	49	355	335	175	120	18
3200	52 1/4	375	355	205	150	45

Data

Run number. 1D

Date. 4/21/56

Type injection point. . . . . .Number One

Location injection point. . . . . .Point A

Location pressure taps. . . . . .ΔP_1 at 1
ΔP_2 at 3
ΔP_3 at 6
ΔP_4 at 7
ΔP_5 at 9

Height of bed from bottom of column, inches . . .49

Rotameter used. .Number Four

Type catalyst . . . . .Used M. S.

Rotameter setting	ΔP_1 (millimeters of water)	ΔP_2	ΔP_3	ΔP_4	ΔP_5	Height of bed (in.)
0.1	516	453	235	162	23	49
0.2	535	467	245	167	27	49
0.3	552	485	251	170	28	49
0.4	570	500	261	176	28	49
0.5	585	512	265	182	29	49
0.6	598	526	276	188	29	49
0.7	616	536	280	190	29	49
0.8	629	552	284	194	30	49
0.9	658	578	300	204	31	49
1.0	672	592	308	211	32	49
1.1	679	596	310	211	32	49
1.2	693	606	314	214	32	49
1.4	732	635	340	230	32	49
1.5	747	-	346	237	33	49
1.6	763	-	350	239	33	49
1.7	777	-	355	245	33	49
1.8	792	-	365	256	33	49
1.9	807	-	372	252	33	49

Run number 1D (continued)

Rotameter setting	ΔP_1	ΔP_2	ΔP_3	ΔP_4	ΔP_5	Height of bed (in.)
	(millimeters of water)					
2.05	822	-	381	261	33	49
2.20	848	-	392	268	33	49
2.4	880	-	408	275	33	49
2.5	892	-	414	284	33	49
2.75	585	-	380	270	65	51
3.0	570	606	395	295	75	52
3.7	580	610	395	296	80	53
4.5	590	633	396	297	100	54
5.5	625	635	397	295	101	55
8.0	628	-	398	296	122	56
5.9	610	640	392	305	120	-
4.5	555	600	375	286	111	55 1/2
3.3	495	555	350	270	100	-
3.0	425	400	380	250	70	53
2.8	375	400	290	255	70	52
2.5	540	320	300	245	65	51 3/4
2.3	550	575	365	250	55	52
2.1	555	575	350	260	60	52
1.9	570	595	350	250	60	52
1.5	525	550	330	250	55	52
1.0	435	515	300	215	50	51 3/4
0.5	420	470	275	200	45	51 1/2
2.0	770	660	350	246	35	49
2.4	825	715	362	255	33	49
2.5	845	735	367	252	33	49
2.7	875	760	378	255	33	49
2.9	900	785	388	260	33	49
3.2	520	-	385	271	70	51 1/2
3.9	(570 600)	-	(380 390)	281	90	52
5.0	(575 615)	-	(385 395)	295	105	55
8.0	(600 610)	-	395	308	135	59
6.0	(545 575)	-	395	310	130	57 1/2
4.0	(295 305)	-	(305 310)	240	70	52 1/2
3.0	(240 260)	-	(205 275)	210	55	51 1/2
2.5	(550 580)	-	365	258	60	51 1/4
2.0	(540 560)	-	340	255	55	51
1.0	(480 500)	-	295	210	45	-

Data

Run number. 2D

Date. 4/23/56

Type injection point. . . . . .Number Two

Location injection point. . . . . .Point A

Location pressure taps. . . . . .ΔP_1 at 1

ΔP_2 at 3

ΔP_3 at 6

ΔP_4 at 7

ΔP_5 at 9

Rotameter used. . . . . .Number Four

Height of bed from bottom of column, inches . . .49

Type catalyst . . . . .Used M. S.

Rotameter setting	ΔP_1 (millimeters of water)	ΔP_2	ΔP_3	ΔP_4	ΔP_5	Height of bed (in.)
0.2	500	405	230	170	26	49
0.5	556	451	258	187	22	49
1.0	631	512	290	208	24	49
1.5	715	580	328	235	26	49
2.0	780	650	326	267	30	49
2.2	805	660	361	266	30	49
2.3	818	676	366	255	30	49
2.5	845	688	370	264	30	49
2.6	860	700	377	265	30	49
2.7	878	715	383	266	30	49
2.8	903	732	390	270	30	49
2.9	913	740	392	270	30	49
3.0	940	758	395	270	30	49
3.2	708	680	395	275	55	51
3.5	(788 794)	680	394	280	65	52
3.7	(690 705)	675	391	282	75	52 1/2
4.0	(630 670)	(660 670)	390	290	87	53

Run number 2D (continued)

Rotameter setting	ΔP_1	ΔP_2	ΔP_3	ΔP_4	ΔP_5	Height of bed (in.)
	(millimeters of water)					
4.5	(690 700)	(665 670)	398	295	90	53 1/2
5.1	(690 705)	675	399	300	105	54 1/2
8.0	(708 714)	676	412	315	150	59
5.1	(620 680)	(600 660)	383	300	120	-
4.5	(640 710)	(655 670)	375	295	100	53
4.0	(575 615)	(645 655)	364	275	100	-
3.5	(565 675)	(625 655)	360	265	80	52 1/2
3.0	(560 680)	(630 660)	350	271	74	-
2.5	(520 590)	-	(330 370)	245	65	51 1/2
2.0	(540 586)	-	(305 350)	215	50	51
1.5	(540 550)	(360 540)	(280 320)	(225 240)	45	51
0.9	485	475	248	170	33	50 1/2

Data

Run number. .3D-1
3D-2

Date. 4/23/56

Type injection points . . . . .Number One

Location injection points . . . . .Point A
Point F

Location pressure taps. . . . . .ΔP_1 at 1

ΔP_2 at 3

ΔP_3 at 6

ΔP_4 at 7

ΔP_5 at 9

Height of bed from bottom of column, inches . . .49

Rotameter used. . . . . 3D-1 Number Three
3D-2 Number Four

Type catalyst . . . . .Used M. S.

Run 3D-1

(Only injection Point F was used)

Rotameter setting	ΔP_1	ΔP_2	ΔP_3	ΔP_4	ΔP_5	Height of bed (in.)
	(millimeters of water)					
1.05	58	74	94	74	8	49
1.8	-	157	208	165	18	49
2.45	-	190	245	212	36	49
3.4	80	100	120 (150)	170 (180)	40	51 1/2
3.0	120	150	175 (200)	170 (180)	30 (50)	51
4.6	-	175	255	220	50	52

Run 3D-2

Rotameter Number Three was set at 3.0 using injection Point F. It was left at this setting throughout run 3D-2.

Run number 3D-1 and 3D-2 (continued)

Rotameter setting	ΔP_1	ΔP_2 (millimeters of water)	ΔP_3	ΔP_4	ΔP_5	Height of bed (in.)
0.6	610	-	300	220	60	52
0.95	655	-	310	227	65	52 1/4
1.5	725	600	320	230	70	52 1/2
2.05	782	660	320	233	72	-
2.4	825	695	322	230	70	53
2.7	865	720	320	230	73	-
2.95	885	745	324	230	70	53
3.2	(510 550)	-	355	260	95	54 1/2

Cut off Rotameter Number Three

Rotameter setting	ΔP_1	ΔP_2 (millimeters of water)	ΔP_3	ΔP_4	ΔP_5	Height of bed (in.)
3.2	(490 570)	-	(356 360)	260	94	54
3.5	(575 660)	(630 710)	(405 330)	(280 290)	(75 82)	-

Using rate 3.5 on Rotameter Number Four, Rotameter Number Three was cut back in at a rate of 3.0

3.5	(480 620)	-	(360 365)	267	(103 107)	-

Data

Run number. 4D

Date. 4/23/56

Type injection point. . . . . Number Three

Location injection point. . . . . Point A

Location pressure taps. . . . . ΔP_1 at 1

ΔP_2 at 3

ΔP_3 at 6

ΔP_4 at 7

ΔP_5 at 9

Height of bed from bottom of column, inches . . . 49

Rotameter used. Number Four

Type catalyst . . . . Used M. S.

Rotameter setting	ΔP_1 (millimeters of water)	ΔP_2	ΔP_3	ΔP_4	ΔP_5	Height of bed (in.)
0.6	650	-	279	190	28	49
0.9	736	-	316	215	33	49
1.35	780	-	340	235	33	49
1.8	910	728	395	268	35	49
2.5	960	800	415	288	35	49
2.9	(610 670)	-	405	288	72	51 3/4
3.6	(650 660)	-	(385 395)	(290 300)	86	53
5.2	(625 665)	650	396	306	110	54 1/2
8.0	(670 685)	(650 666)	(400 405)	311	140	58
5.0	(620 660)	-	(380 390)	294	110	56 1/2
3.5	(560 650)	-	(340 360)	255	92	53

Run number 4D (continued)

Rotameter setting	ΔP_1 (millimeters of water)	ΔP_2	ΔP_3	ΔP_4	ΔP_5	Height of bed (in.)
3.0	510 (630)	-	340	267 (275)	81	52 3/4
2.5	440 (570)	-	333 (360)	195 (215)	75	52
2.0	580 (620)	-	296 (310)	205 (214)	50	52
1.5	525 (555)	-	185	190	48	-

Data

Run number. 1E

Date. 4/24/56

Type injection point. . . . . .Number One

Location injection point. . . . . .ΔP_1 at 1

ΔP_2 at 3

ΔP_3 at 6

ΔP_4 at 7

ΔP_5 at 9

Height of bed from bottom of column, inches 49

Rotameter used. .Number Four

Type catalyst . . . . .Used M. S.

Catalyst flow rate. . . . . .3 inches per minute

Rotameter setting	ΔP_1 (millimeters of water)	ΔP_2	ΔP_3	ΔP_4	ΔP_5
0.5	625	-	300	210	30
0.9	640	-	316	215	31
1.3	625	-	310	215	32
2.1	645	-	305	210	35
3.3	600	-	260	170	-
5.8	650	-	290	210	38
8.3	660	-	310	215	40
1.8	590	-	-	-	-
1.65	590	-	-	-	-
2.4	610	-	-	-	-
2.7	590	-	-	-	-

Data

Run number. .2E

Date. 4/24/56

Type injection point. . . . . .Number Two

Location injection point. . . . . .Point A

Location pressure taps. . . . . .ΔP_1 at 1

ΔP_3 at 3

Rotameter used. . . . . .Number Four

Type catalyst . . . . .Used M. S.

Rotameter setting	ΔP_1 (millimeters of water)
0.4	560
0.9	590
1.3	590
1.7	620
1.9	640
2.2	570
2.5	650
2.9	620
3.3	650
3.7	655
4.4	660

Data

Run number. 3E

Date. 4/24/56

Type injection point. . . . . .Number Three

Location injection point. . . . . .Point A

Location pressure taps. . . . . .ΔP_1 at 1

ΔP_3 at 6

Rotameter used. .Number Four

Height of bed from bottom of column, inches . . .49

Type catalyst . . . . .Used M. S.

Rotameter setting	ΔP_1 (millimeters of water)	ΔP_3
0.5	465	195
0.8	490	215
1.1	530	230
1.5	575	250
2.0	635	270
2.4	670	280
2.7	680	295
3.0	595	295
3.5	580	-
5.0	660	-

Data

Run number. 1F

Date. 4/23/56

Type injection point. . . . . .Number One

Location injection point. . . . . .Point A

Location pressure taps. . . . . .ΔP_1 at 1

ΔP_2 at 3

ΔP_3 at 6

ΔP_4 at 7

ΔP_5 at 9

Rotameter used. .Number Four

Rotameter was set 3.0 with no catalyst in the tube.
Catalyst was added in 600 grams increments.

Type catalyst . . . . .Used M. S.

Rotameter setting	Weight of catalyst in tube, grams	ΔP_1	ΔP_2	ΔP_3 (millimeters of water)	ΔP_4	ΔP_5
3.0	600	5	0	0	0	0
3.0	1200	35	0	0	0	0
3.0	1800	100	66	0	0	0
3.0	2400	190	145	0	0	0
3.0	3000	260	220	0	0	0
3.0	3600	320	310	66	0	0
3.0	4200	(388, 395)	380	168	70	0
3.0	4800	(405, 500)	-	(250, 270)	160	0
3.0	5530	(490, 560)	-	(360, 380)	130	70

Data

Run number. 1G

Date. 5/25/56

Type injection point. . . . . .Number Three

Location injection point. . . . . .Point A

Location pressure taps. . . . . .ΔP_1 at 1

ΔP_3 at 6

Rotameter used. . . . . .Number Four

Height of bed from bottom of column, inches 49

Type catalyst . . . . .Used M. S.

Catalyst flow rate. . . . .(0.5) inches per minute

Rotameter setting	ΔP_1 (millimeters of water)	ΔP_3
0.5	730	330
1.0	740	322
1.5	730	328
2.0	732	328
2.5	733	328
3.5	734	329
0.8	738	322
0.2	722	325
1.7	729	-

Data

Run number. 1H

Date. 5/25/56

Type injection point. . . . . .Number Three

Location injection point. . . . . .Point A

Location pressure taps. . . . . .ΔP_1 at 1

ΔP_3 at 6

Rotameter used. . . . . .Number Four

Height of bed from bottom of column, inches 49

Type catalyst . . . . .Used M. S.

Catalyst flow rate. . . . .(1.5) inches per minute

Rotameter setting	ΔP_1 (millimeters of water)	ΔP_3
0.5	736	320
1.0	744	325
1.5	736	322
2.0	738	316
2.5	739	319
0.8	739	319

Data

Run number. 11

Date. 5/25/56

Type injection point. . . . . .Number Three

Location injection point. . . . . .Point A

Location pressure taps. . . . . .ΔP_1 at 1
ΔP_3 at 6

Rotameter used. . . . . .Number Four

Height of bed from bottom of column, inches 49

Type catalyst .New M. S.

Catalyst flow rate. . . . .(1.5) inches per minute

Rotameter setting	ΔP_1 (millimeters of water)	ΔP_3
0.3	430	190
0.5	427	183
0.7	432	185
0.9	431	-
1.5	438	186
2.9	439	187
0.4	428	185
1.2	435	188
0.1	426	-

Data

Run number. 1J

Date. 5/25/56

Type injection point. . . . . .Number One

Location injection point. . . . . .Point A

Location pressure taps. . . . . .ΔP_1 at 1
ΔP_3 at 2

Rotameter used. . . . . .Number Four

Height of bed from bottom of column, inches . . .49

Type catalyst . . . . .New M. S.

Catalyst flow rate. . . . .(0.75) inches per minute

Rotameter setting	ΔP_1 (millimeters of water)	ΔP_3
1.3	409	350
0.3	408	360
0.6	405	361
0.8	404	356
1.1	405	363
1.5	415	370
2.5	417	372

Data

Run number. 1K

Date. 5/25/56

Type injection point. . . . . .Number Two

Location injection point. . . . . .Point A

Location pressure taps. . . . . .ΔP_1 at 1
ΔP_2 at 2

Rotameter used. . . . . .Number Four

Height of bed from bottom of column, inches 49

Type catalyst . . . . .New Catalyst

Catalyst flow rate. . . . .(0.75) inches per minute

Rotameter setting	ΔP_1 (millimeters of water)	ΔP_2
0.2	410	350
0.3	411	355
0.5	418	365
0.6	425	360
0.7	428	360
0.9	416	360
1.2	422	-
3.8	430	365

Data

Run number. 1L

Date. 5/25/56

Type injection point. . . . . .Number Two

Location injection point. . . . . .Point A

Location pressure tap . . . . .ΔP_1 at 1

Rotameter used. .Number Four

Height of bed from bottom of column, inches 49

Type catalyst . . . . .Used M. S.

Catalyst flow rate. . . . . .4 inches per minute

Rotameter setting	ΔP_1 (millimeters of water)
0.1	740
0.3	735
0.5	748
0.7	730
1.4	749
0.9	748
2.0	755
3.1	756
0.4	738
0.2	750 or 745
0.7	732

Data

Run number. 1M

Date. 5/25/56

Type injection point. . . . . .Number One

Location injection point. . . . . .Point A

Location pressure tap . . . . .ΔP_1 at 1

Rotameter used. . . . . .Number Four

Height of bed from bottom of column, inches 49

Type catalyst .Used M. S.

Catalyst flow rate. . . . . .4 inches per minute

Rotameter setting	ΔP_1 (millimeters of water)
0.1	750
0.2	757
0.3	745
0.4	748
0.5	752
0.7	758
2.5	760
4.1	759
1.5	759

Data

Run number. 1N

Date. 5/25/56

Type injection point. . . . . .Number One

Location injection point. . . . . .Point A

Location pressure tap . . . . .ΔP_1 at 1

Rotameter used. .Number Four

Height of bed from bottom of column, inches 49

Type catalyst . . . . .New M. S.

Catalyst flow rate. . . . . .4 inches per minute

Rotameter setting	ΔP_1 (millimeters of water)
0.1	420
0.2	415
0.3	430
0.4	405
0.5	415
0.6	423
0.8	425
1.5	428

Data

Run number. 10

Date. 5/25/56

Type injection point. . . . . .Number Two

Location injection point. . . . . .Point A

Location pressure tap . . . . .ΔP_1 at 1

Rotameter used. .Number Four

Height of bed from bottom of column, inches 49

Type catalyst . . . . .New M. S.

Catalyst flow rate. . . . . .4 inches per minute

Rotameter setting	ΔP_1 (millimeters of water)
0.1	430
0.2	431
0.3	410
0.5	430
0.8	432
1.5	435

APPENDIX D

SAMPLE CALCULATIONS

SAMPLE CALCULATIONS

Diameter of column, inside, inches. 3.5

Area of column, inside, square feet 0.06678

Factor from cu. ft./min to ft./hr. = 0.899

$$\text{ft./hr.} = \frac{\text{cu. ft.}}{\text{min.}} \times \frac{60 \text{ min.}}{1 \text{ hr.}} \times \frac{1}{0.06678 \text{ sq. ft.}} = \text{ft./hr.}$$

Catalyst rate. . . . . 3 inches per minute or 0.25 feet per minute

0.06678 x 0.25 = .0167 (cu. ft./min.) of catalyst volume displacement

Catalyst velocity. . . . . feet/hour

$$\text{ft./hr.} = \frac{3 \text{ in.}}{\text{min.}} \times \frac{60 \text{ min.}}{1 \text{ hr.}} \times \frac{1 \text{ ft.}}{12} = 15 \text{ ft./hr.}$$

Sample Calculation:

Run Number. 1A

Rotameter setting	cu.ft./min.	ft./hr.	ΔP_1 (MM of HOH)
1.80	0.105	94.3	360
1.60	0.09	80.9	370
1.10	0.055	49.5	360
0.90	0.04	35.9	360

DERIVATION OF EQUATION (14)

Let:

F_g = the gravitational accelerating force (dynes)

F_r = the resisting upward drag force (dynes)

u = relative velocity between the main body of fluid and particle or body cm./sec.

u_T = terminal gravitational settling velocity of body or particle relative to fluid cm./sec.

$$Fg = g_L\, M_p \,/\frac{\rho p - \rho}{p}/ \qquad (15)$$

g_L = local acceleration due to gravity, cm./sec.^{2}

M_p = mass of particle, grams. $\pi \rho p D_p{}^3/6$

ρp = true density of particle (gms./cu.cm.)

ρ = density of medium (gm./cu.cm.)

Fg represent the force down.

$$Fr = (\rho \frac{u^2}{2}) Ap^C \qquad (16)$$

ρ = density of bed, gm./cu.cm.

u = relative velocity between main body of fluid and particle or body, cm./sec.

Ap = area of projected plan $\pi D_p{}^2/4$, cm.^{2}

c = drag coefficient (dimensionless)

Fr represents the force up.

When Fr is equal to Fg the terminal velocity has been reached and then u = u_T. Therefore:

$$gLM_p \,/\frac{(\rho p - \rho)}{p}/ = \rho \frac{u^2}{2} \quad A_p c$$

or solving for u:

$$u = \sqrt{\frac{2\, g^L\, Mp(\rho p - \rho)}{\rho \rho p \quad A_p c}} \quad \text{or} \quad u_T = \sqrt{\frac{2gL\; Mp\; (\rho p - \rho)}{\rho \rho p \; A_p c}} \qquad (17)$$

$$A_p = \pi Dp^{2}/4$$

$$M_p = \rho p\, \pi\, Dp^{3}/6$$

$$Fr = \pi Dp^2 c \rho u^2/8 \qquad (18)$$

By substitution and solving for u_T:

$$u_T = \sqrt{\frac{4g^L\; D_p\; (\rho p - \rho)}{3 \rho c}} \qquad (19)$$

For streamline flow when the inertial terms are negligible the following relation holds:

$$F_r = 3 \pi \mu u\, D_p \qquad (20)$$

This is recognized as Stokes Law.

Converting the velocity needed for fluidization into terms of Reynolds Number:

$$N_{Re} = Du\rho/\mu \tag{21}$$

D = diameter of particle, cm.

u = velocity of air, cm./sec.

ρ = density of particle, gm./cu.cm.

μ = viscosity of air, gm./cm.sec.

$$N_{Re} = \frac{0.0062 \text{ cm.} \times .193 \times 2.56}{0.018}$$

$$= 0.1705$$

This puts the flow in the streamline range; therefore, Stokes relation should hold.

Substitution of Equation 18 into Equation 16 gives the following drag coefficient:

$$C = \frac{24\,\mu}{\rho\, u D_p} = 24/N_{Re} \tag{22}$$

The combination of Equation 19 and Equation 22 gives the following:

$$u_T = \frac{g\, D_p^2\, (\rho p - \rho)}{18\,\mu} \tag{23}$$

Substitution of data into Equation 23 gives:

$$u_T = \frac{980 \times 0.0000384 \times (2.54-0.001)}{18 \times 0.018}$$

$$u_T = 0.295 \text{ cm./sec.}$$

$$= 34.8 \text{ ft./hr.}$$

The terminal velocity of 34.8 feet per hour is one and one-half of that velocity required for fluidzation.

The following equation holds for the data presented:

$$V_n = 2/3\ u_T + V_p \tag{14}$$

V_n = velocity required for fluidization

u_T = terminal velocity

V_p = net velocity of particle with respect to walls of the vessel.

Data points from Equation 14 are plotted in Figure 10.

APPENDIX E

GRAPHS

Pressure Drop plotted as a function of Gas Velocity on Runs 3A through 10.

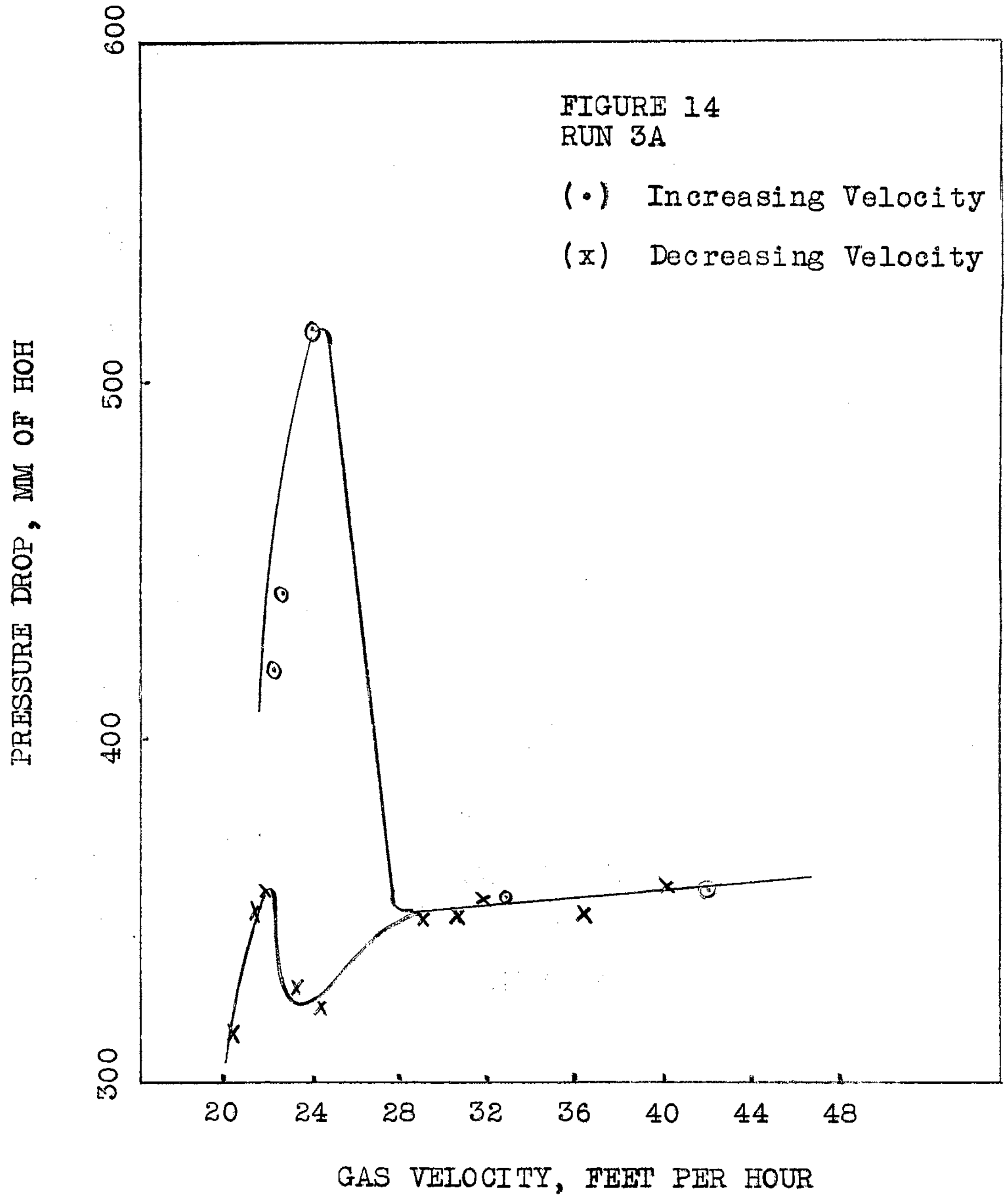


FIGURE 14
RUN 3A
(•) Increasing Velocity
(x) Decreasing Velocity
PRESSURE DROP, MM OF HOH
300
400
500
600
20
24
28
32
36
40
44
48
GAS VELOCITY, FEET PER HOUR

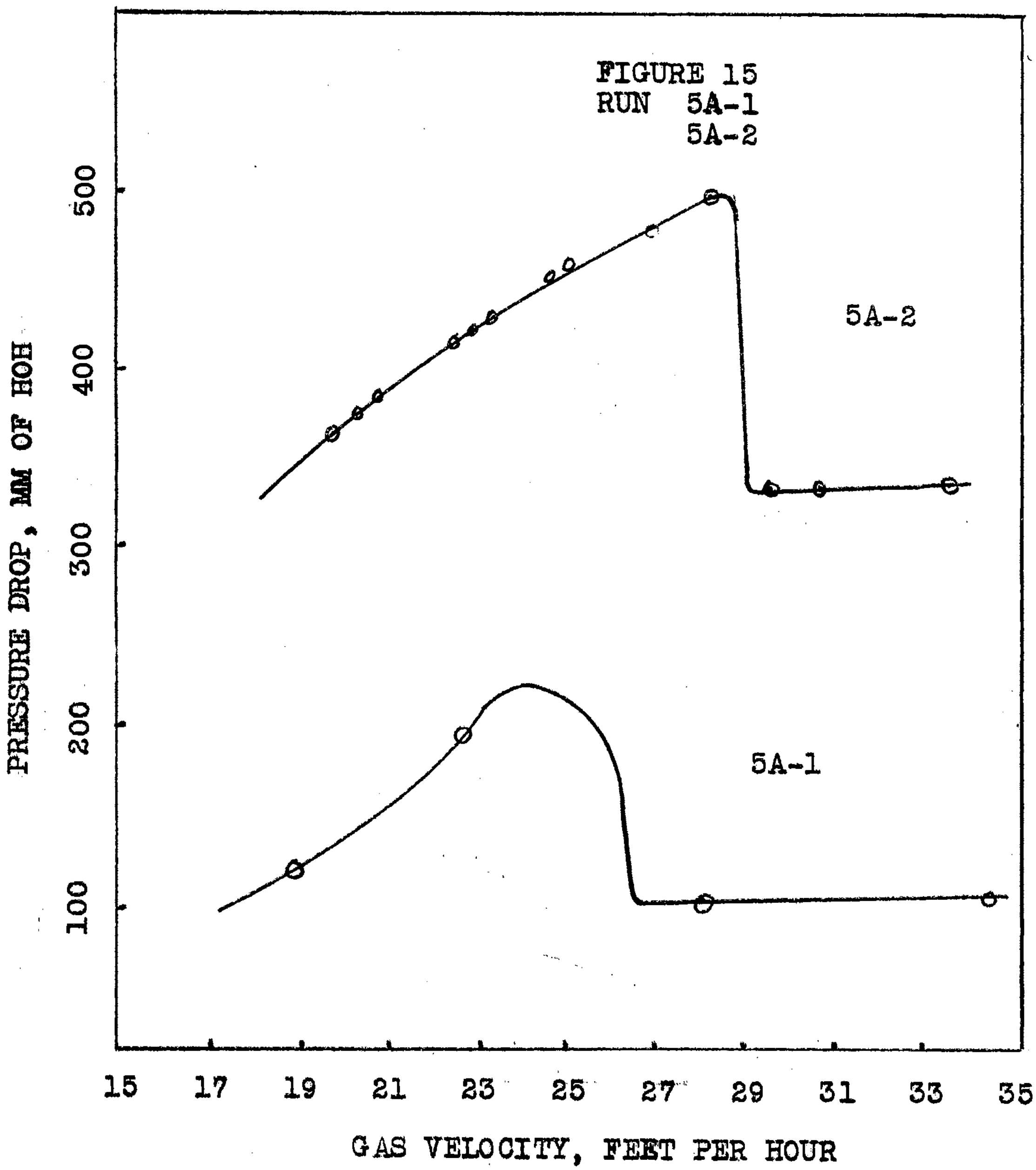


FIGURE 15
RUN 5A-1
5A-2
5A-2
5A-1
PRESSURE DROP, MM OF HOH
100
200
300
400
500
15
17
19
21
23
25
27
29
31
33
35
GAS VELOCITY, FEET PER HOUR

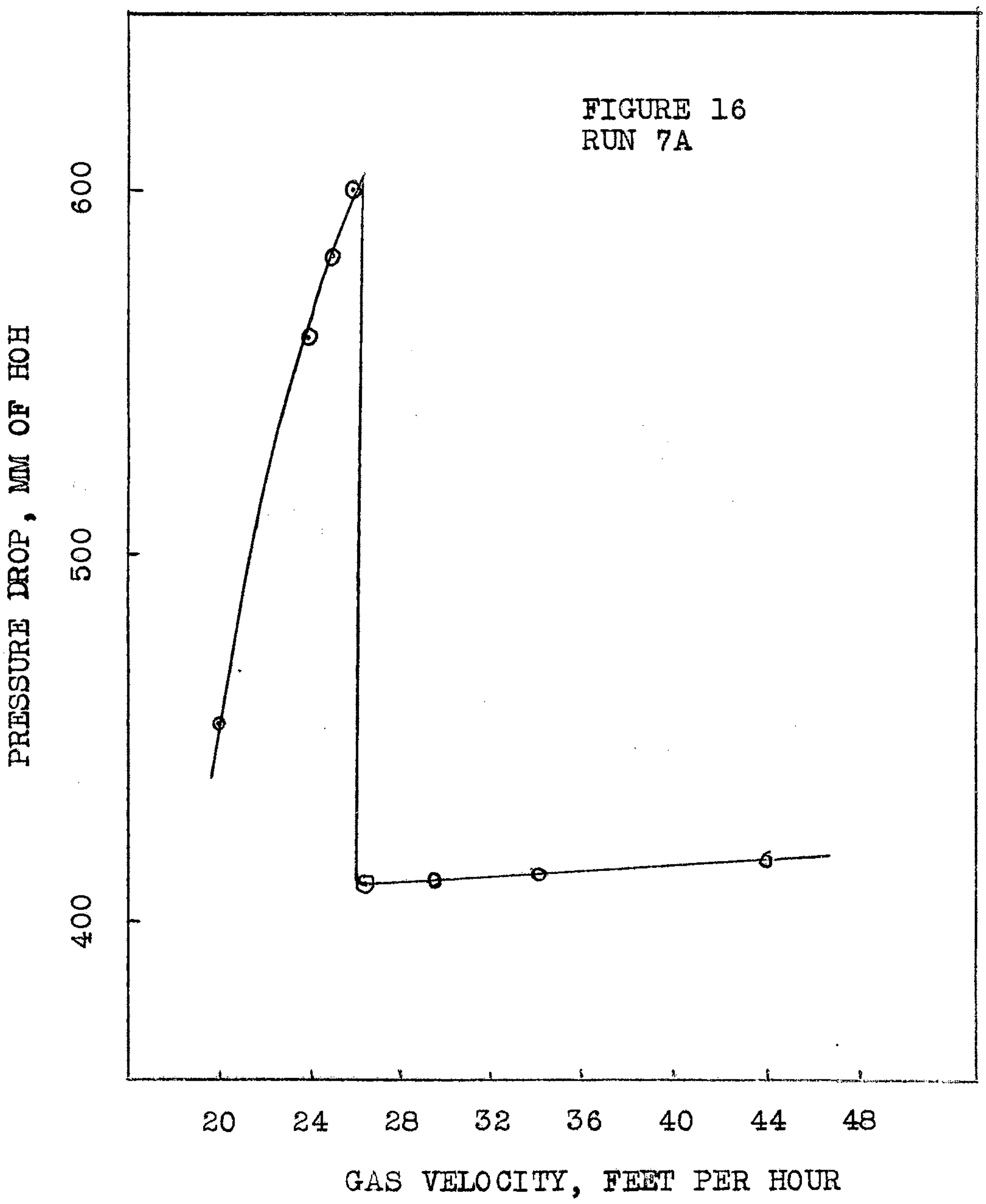


FIGURE 16
RUN 7A
PRESSURE DROP, MM OF HOH
600
500
400
20
24
28
32
36
40
44
48
GAS VELOCITY, FEET PER HOUR

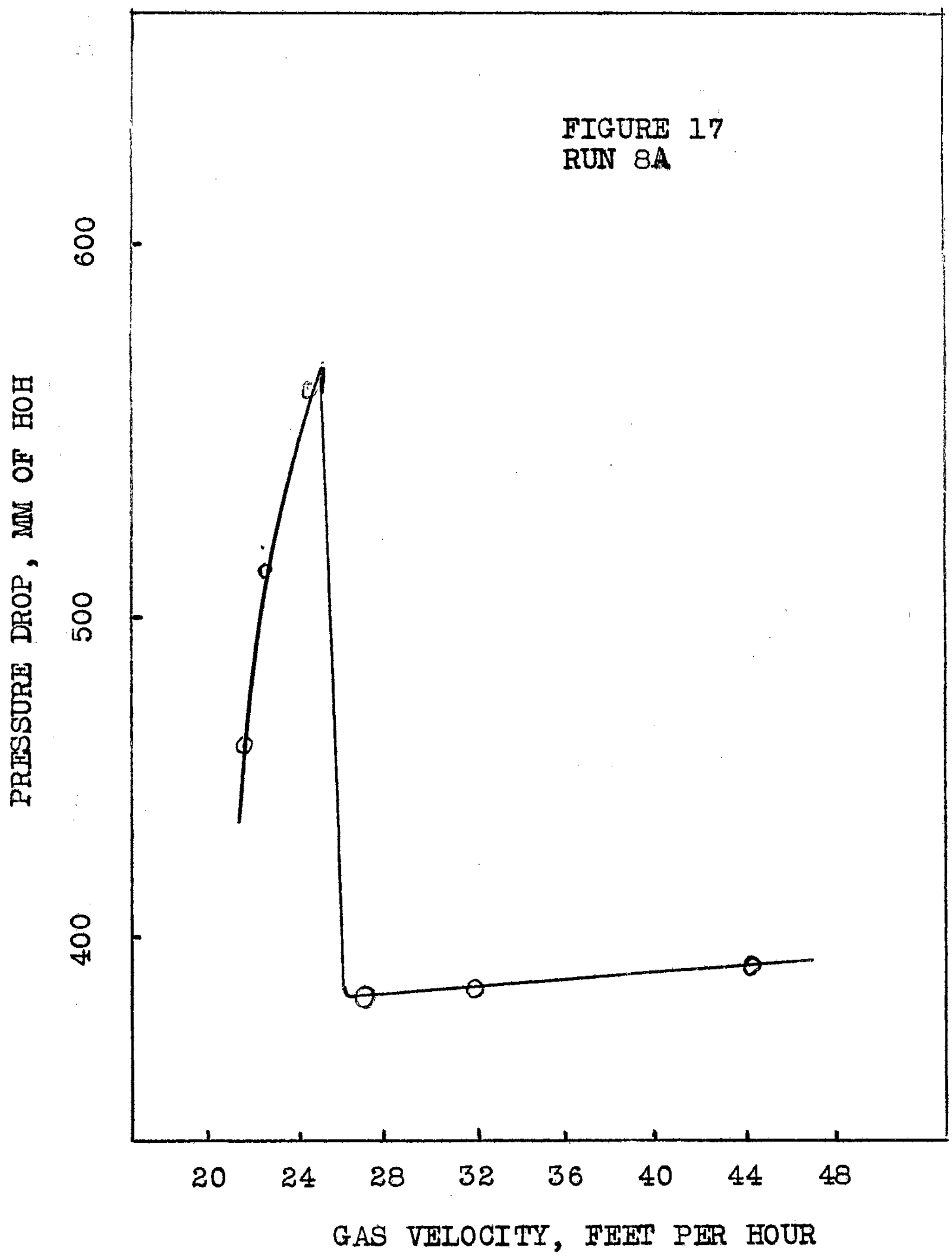


FIGURE 17
RUN 8A
PRESSURE DROP, MM OF HOH
600
500
400
20
24
28
32
36
40
44
48
GAS VELOCITY, FEET PER HOUR

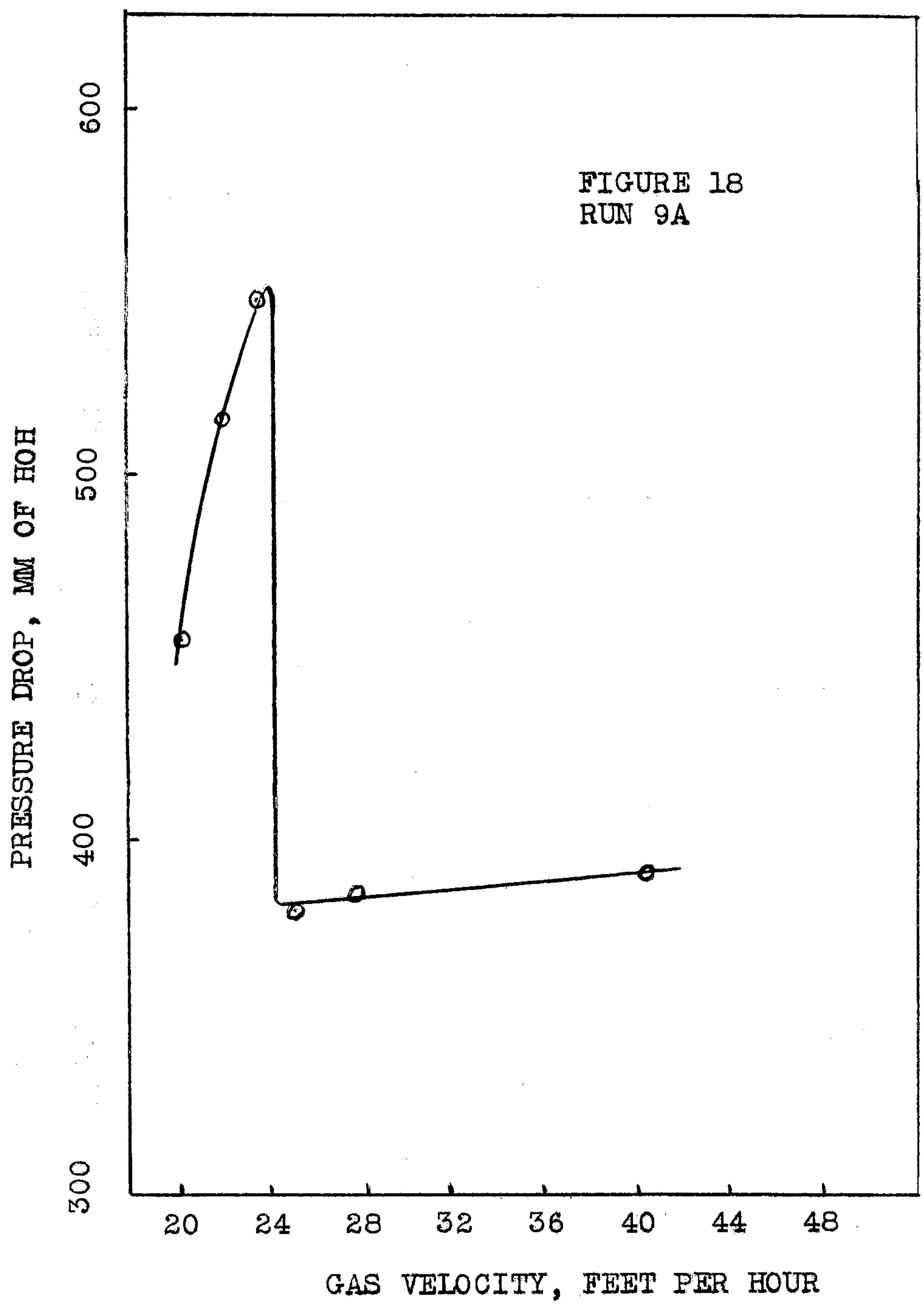


FIGURE 18
RUN 9A
PRESSURE DROP, MM OF HOH
600
500
400
300
20
24
28
32
36
40
44
48
GAS VELOCITY, FEET PER HOUR

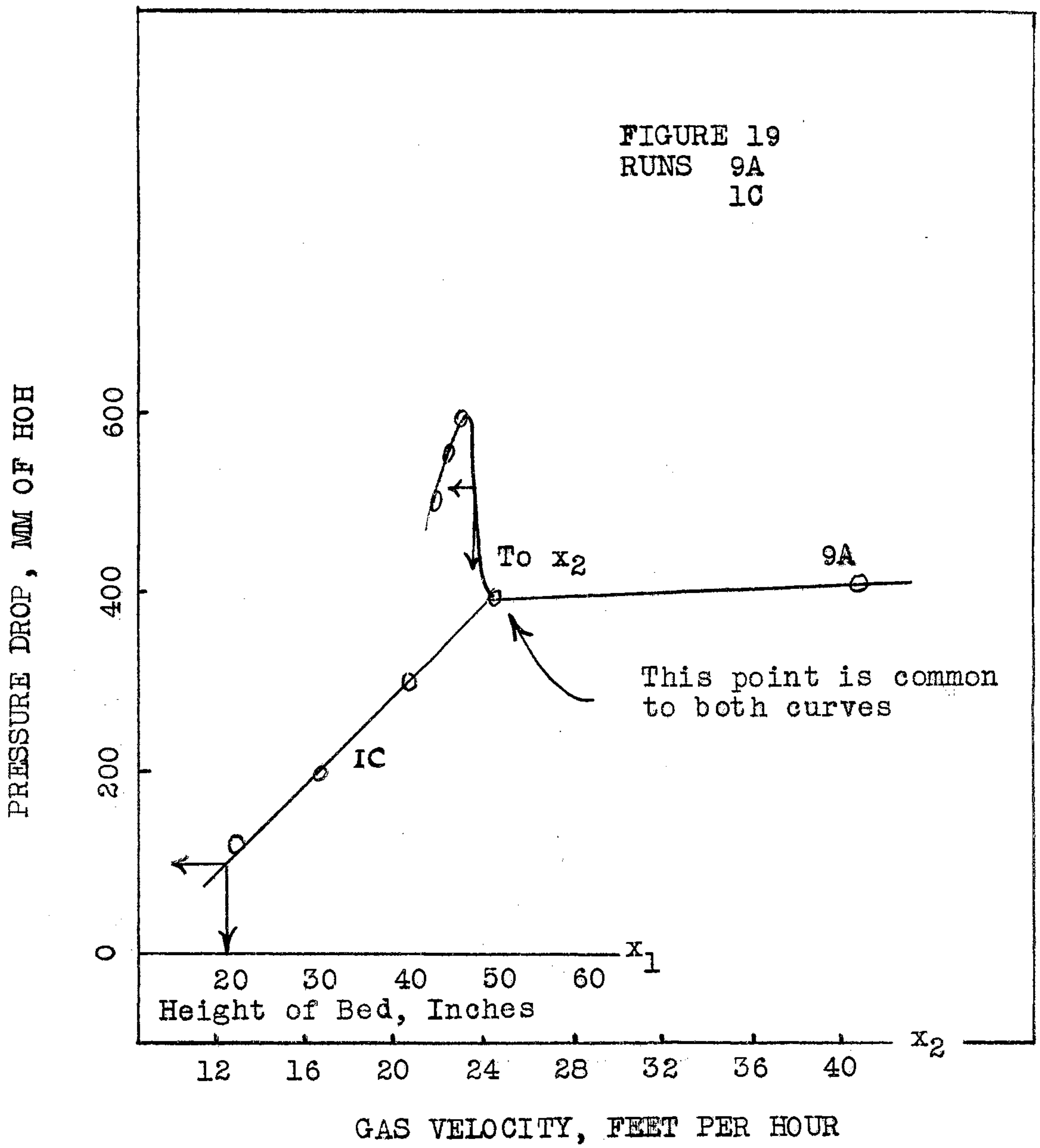


FIGURE 19
RUNS 9A
1C
PRESSURE DROP, MM OF HOH
0
200
400
600
To x_2
9A
IC
This point is common
to both curves
x_1
20 30 40 50 60
Height of Bed, Inches
x_2
12 16 20 24 28 32 36 40
GAS VELOCITY, FEET PER HOUR

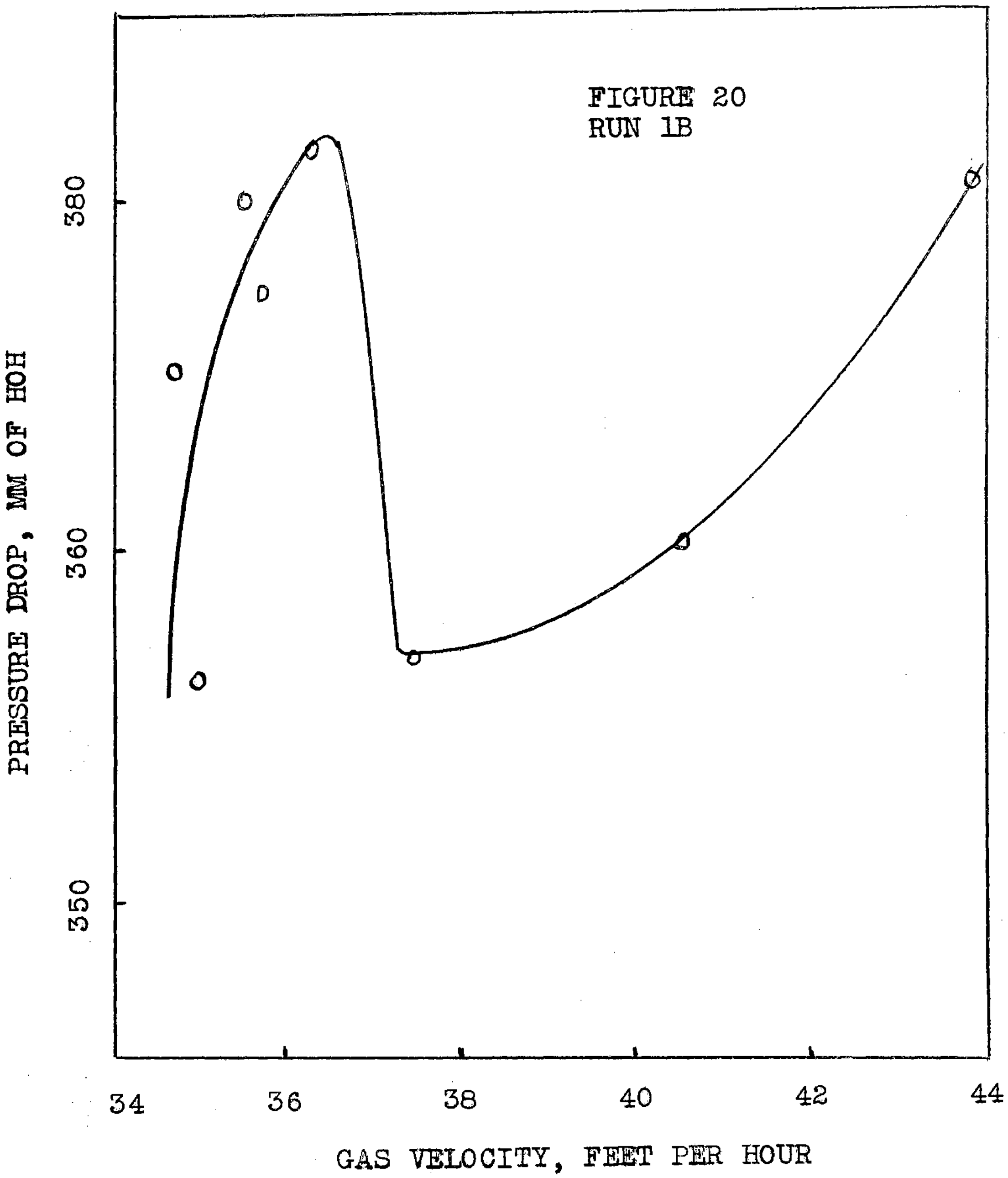


FIGURE 20
RUN 1B
PRESSURE DROP, MM OF HOH
380
360
350
34
36
38
40
42
44
GAS VELOCITY, FEET PER HOUR

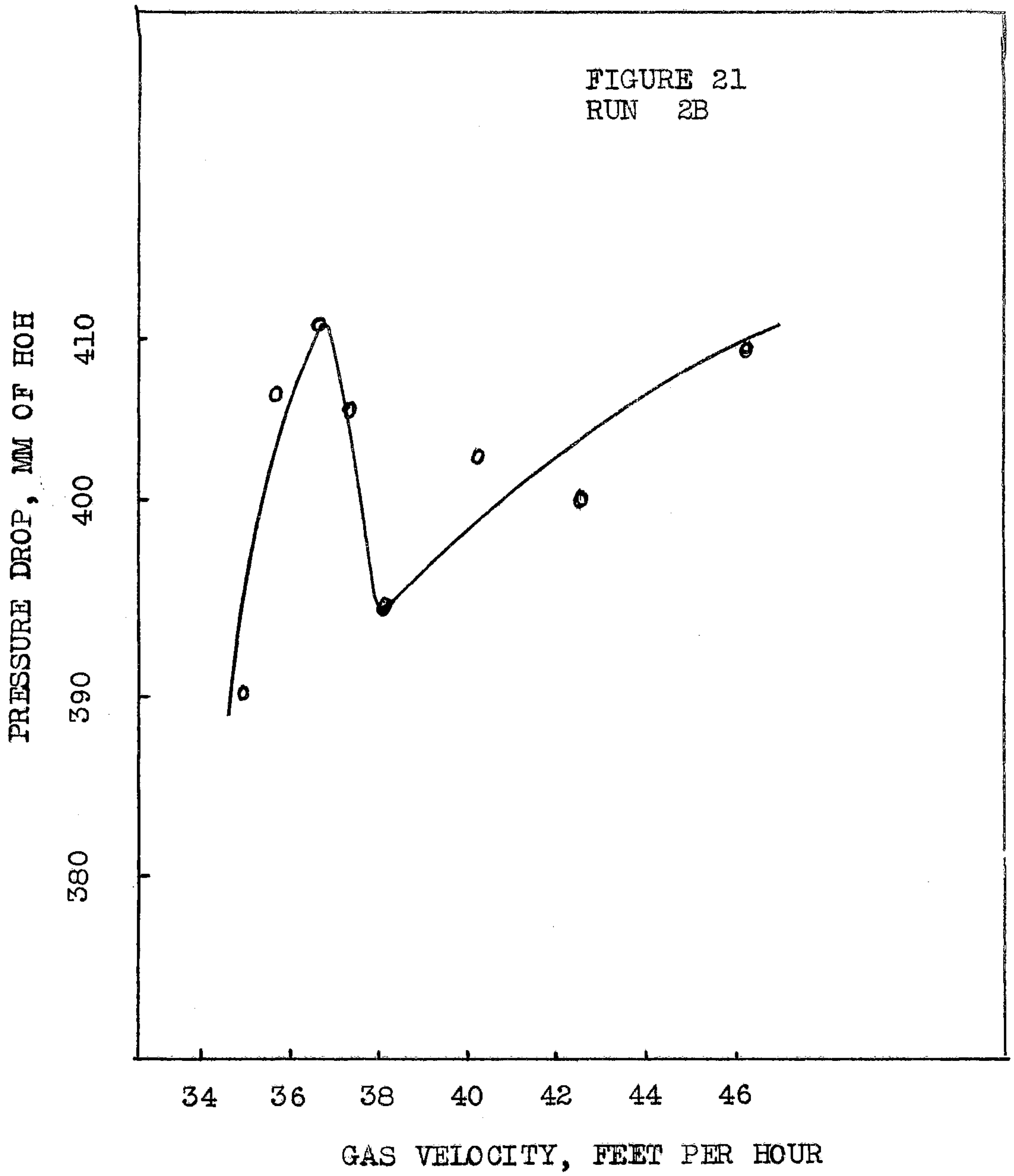


FIGURE 21
RUN 2B
PRESSURE DROP, MM OF HOH
410
400
390
380
34
36
38
40
42
44
46
GAS VELOCITY, FEET PER HOUR

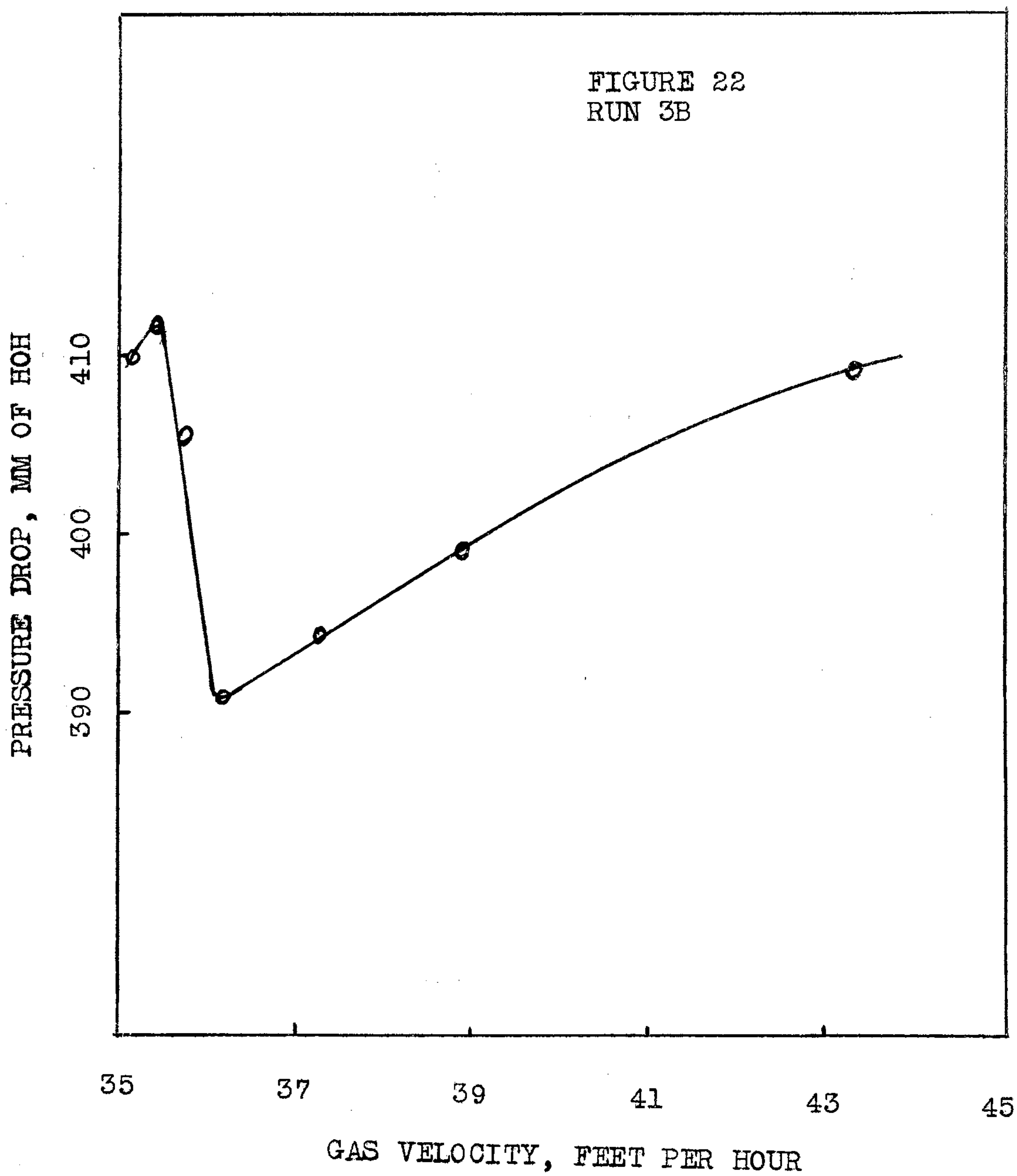


FIGURE 22
RUN 3B
PRESSURE DROP, MM OF HOH
410
400
390
35
37
39
41
43
45
GAS VELOCITY, FEET PER HOUR

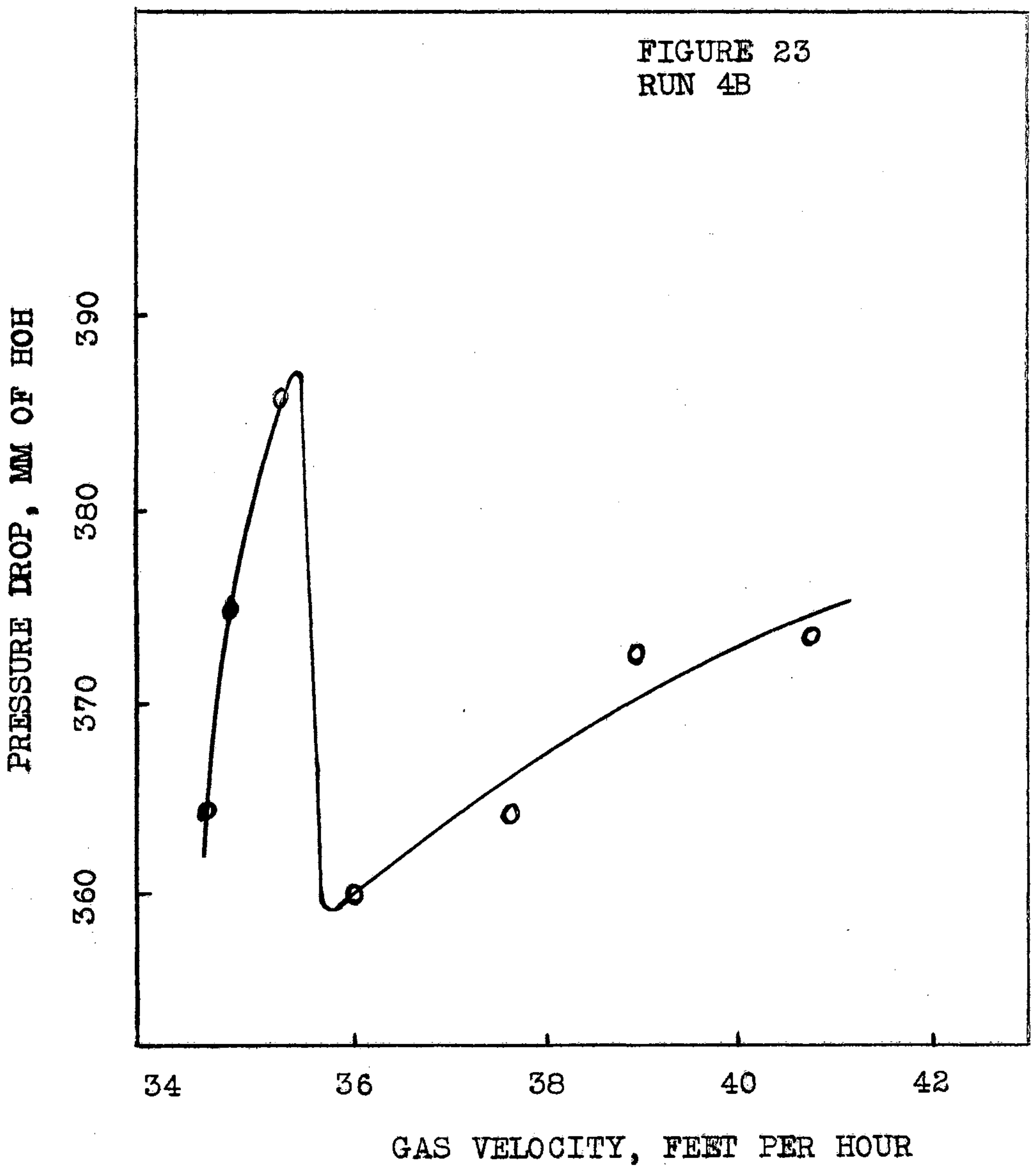


FIGURE 23
RUN 4B
PRESSURE DROP, MM OF HOH
360
370
380
390
34
36
38
40
42
GAS VELOCITY, FEET PER HOUR

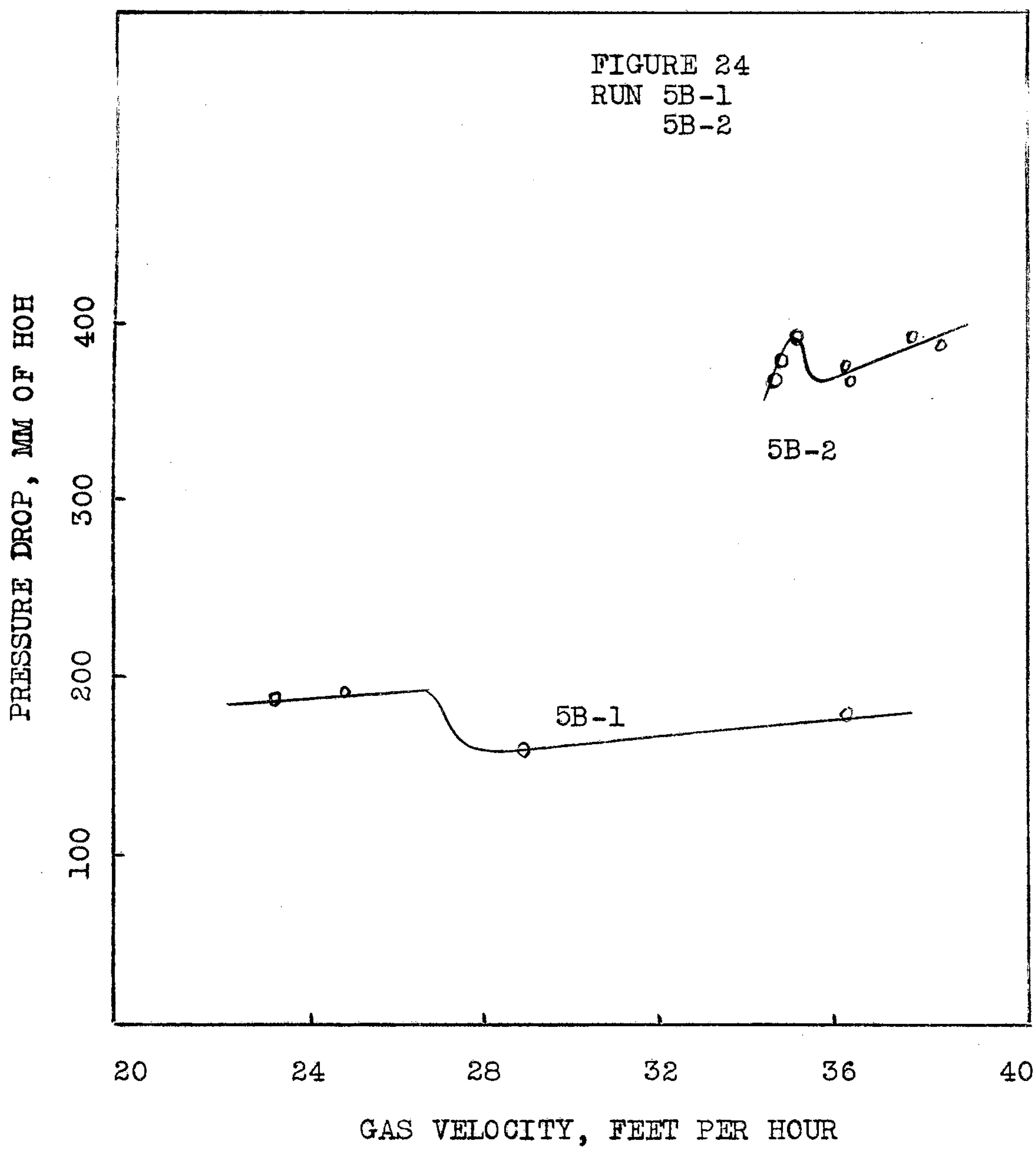


FIGURE 24
RUN 5B-1
5B-2
5B-2
5B-1
PRESSURE DROP, MM OF HOH
100
200
300
400
20
24
28
32
36
40
GAS VELOCITY, FEET PER HOUR

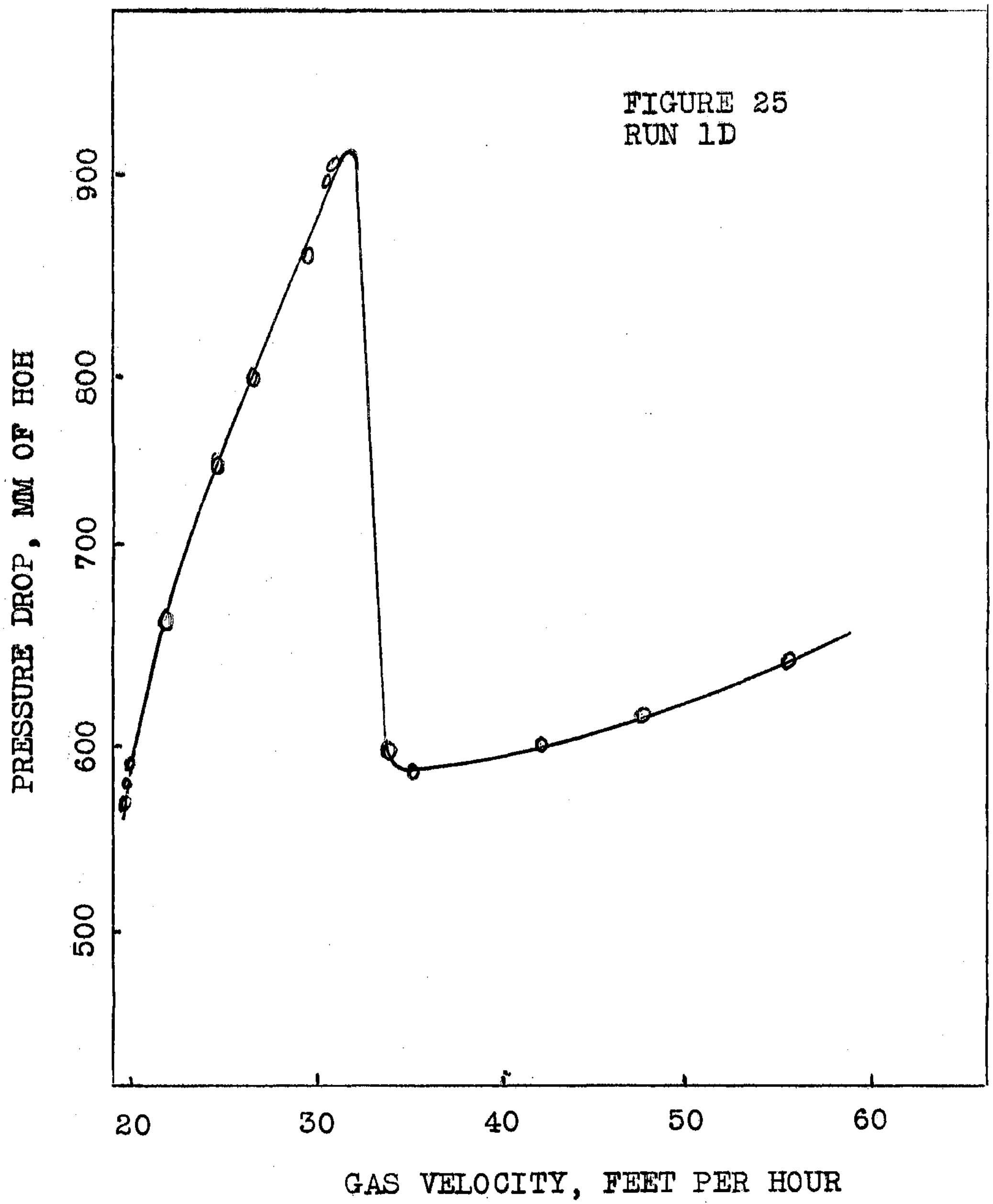


FIGURE 25
RUN 1D
PRESSURE DROP, MM OF HOH
500
600
700
800
900
20
30
40
50
60
GAS VELOCITY, FEET PER HOUR

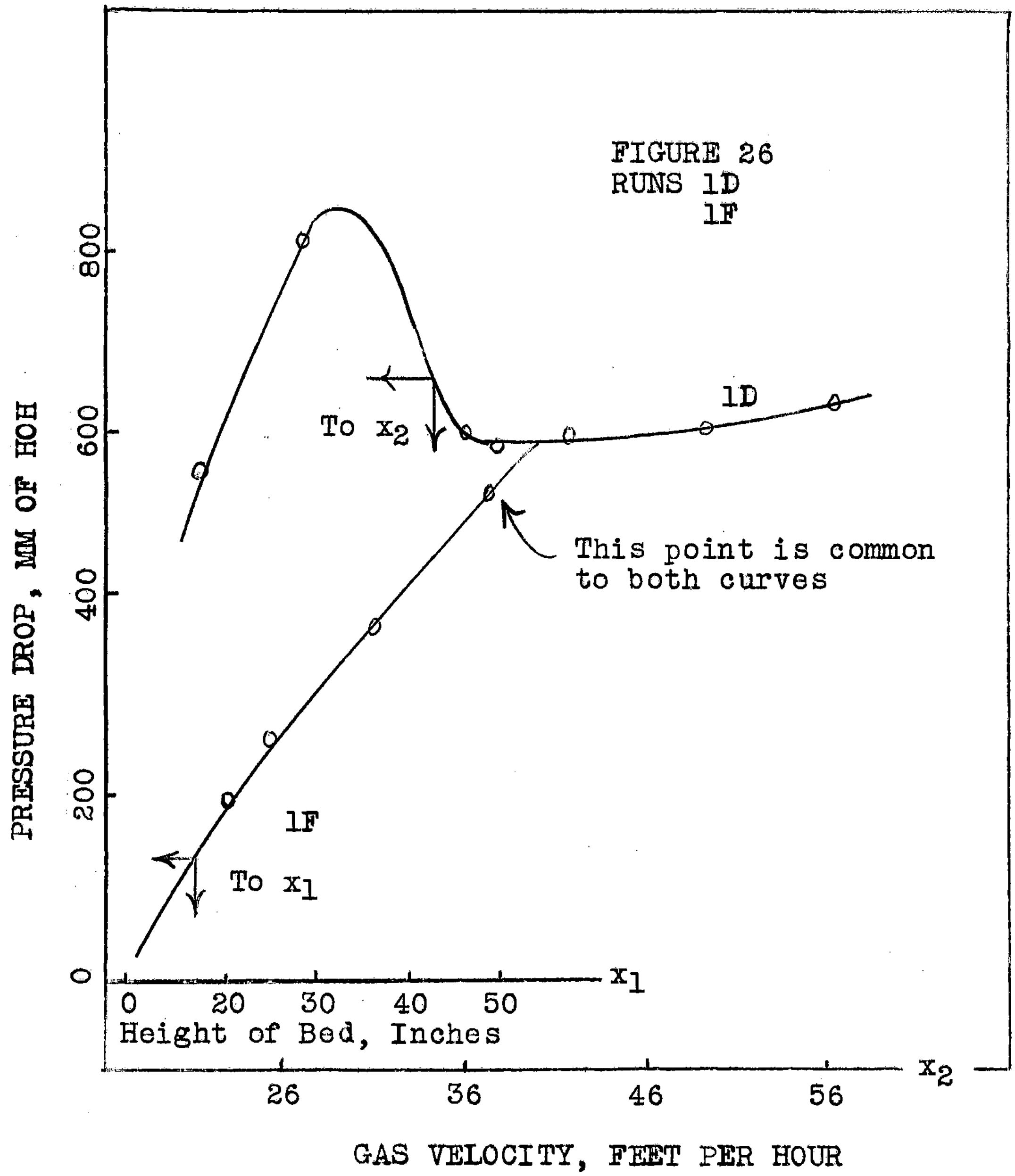


FIGURE 26
RUNS 1D
1F
PRESSURE DROP, MM OF HOH
800
600
400
200
0
1D
1F
To x_2
To x_1
This point is common to both curves
x_1
0
20
30
40
50
Height of Bed, Inches
x_2
26
36
46
56
GAS VELOCITY, FEET PER HOUR

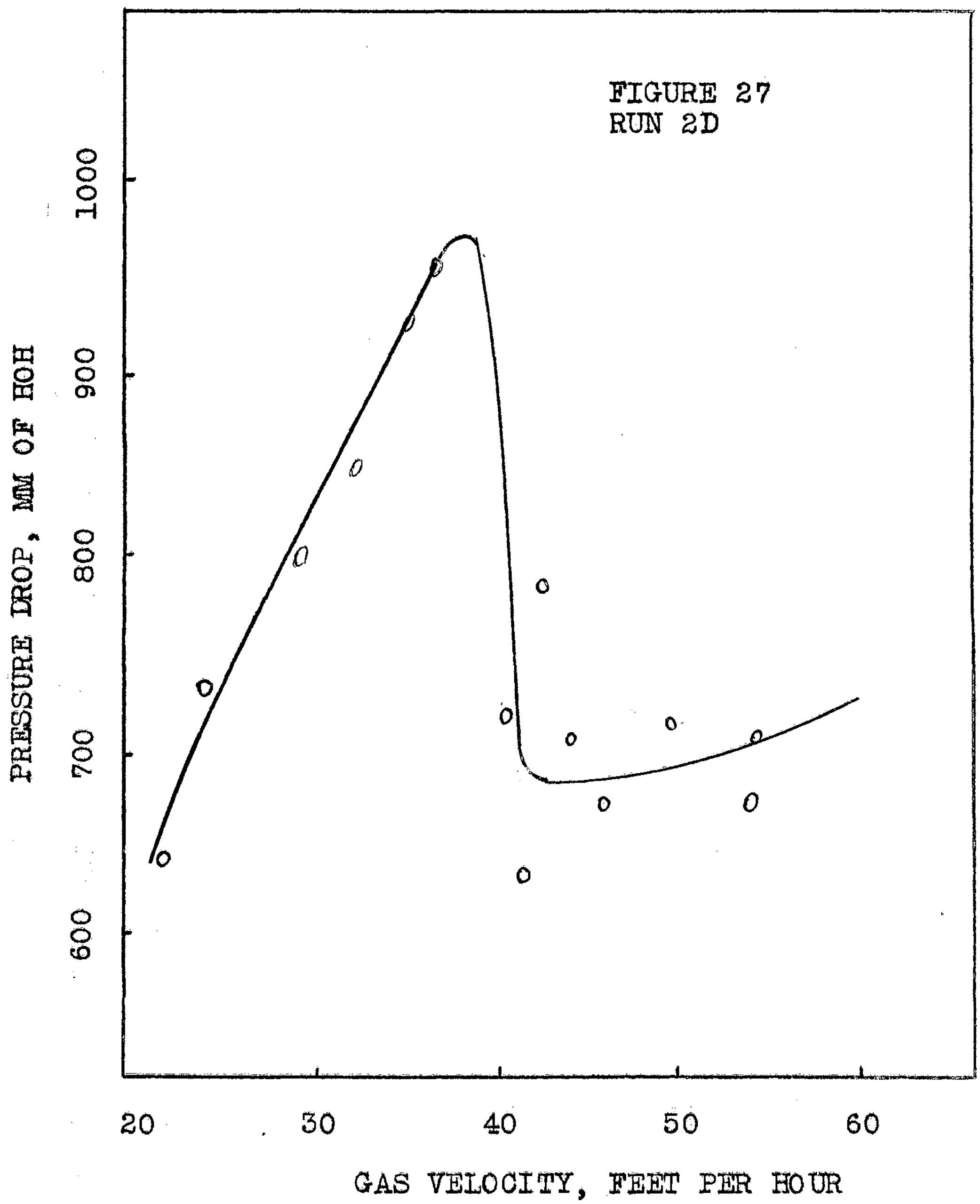


FIGURE 27
RUN 2D
PRESSURE DROP, MM OF HOH
1000
900
800
700
600
20
30
40
50
60
GAS VELOCITY, FEET PER HOUR

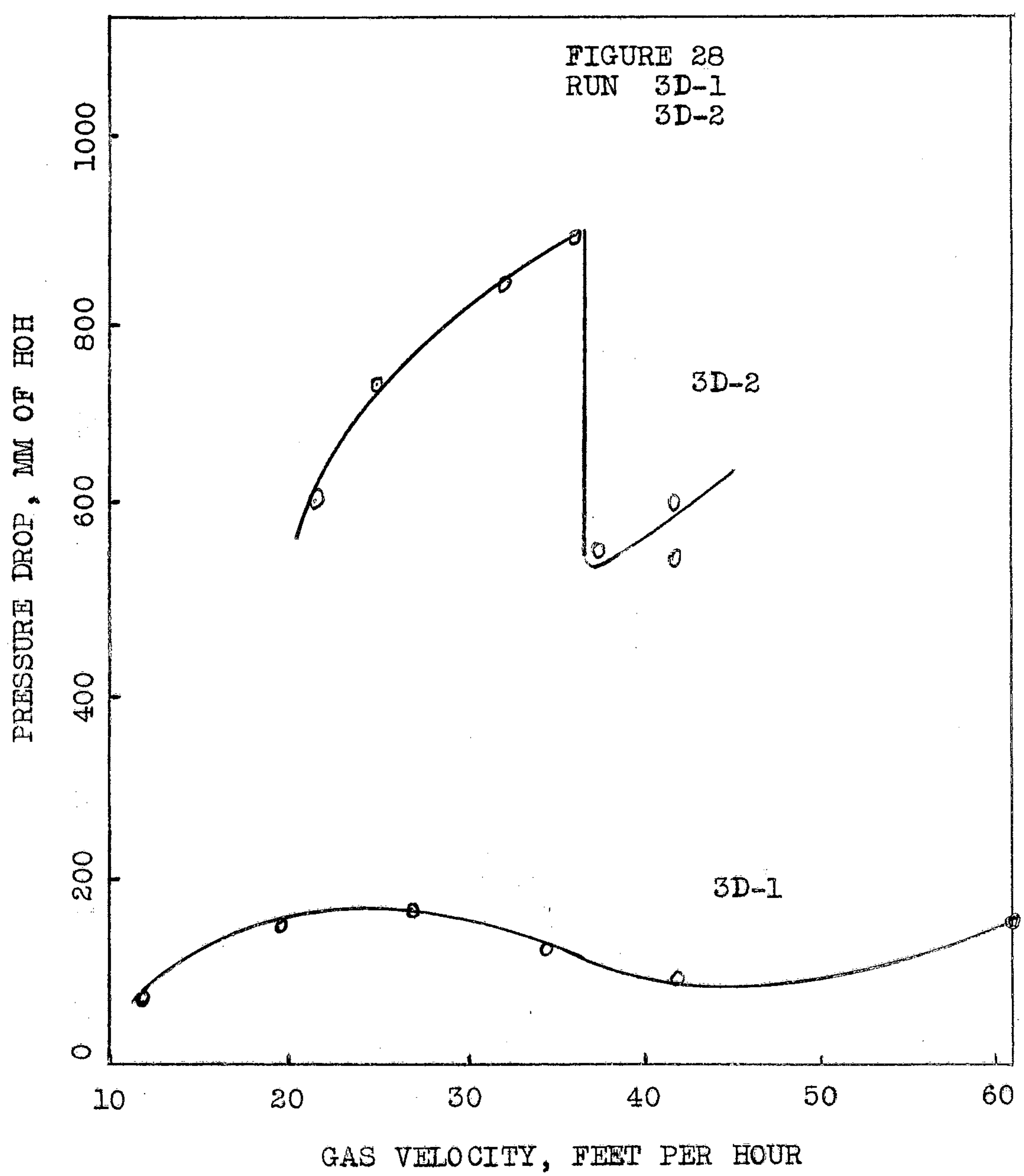


FIGURE 28
RUN 3D-1
3D-2
3D-2
3D-1
PRESSURE DROP, MM OF HOH
0
200
400
600
800
1000
10
20
30
40
50
60
GAS VELOCITY, FEET PER HOUR

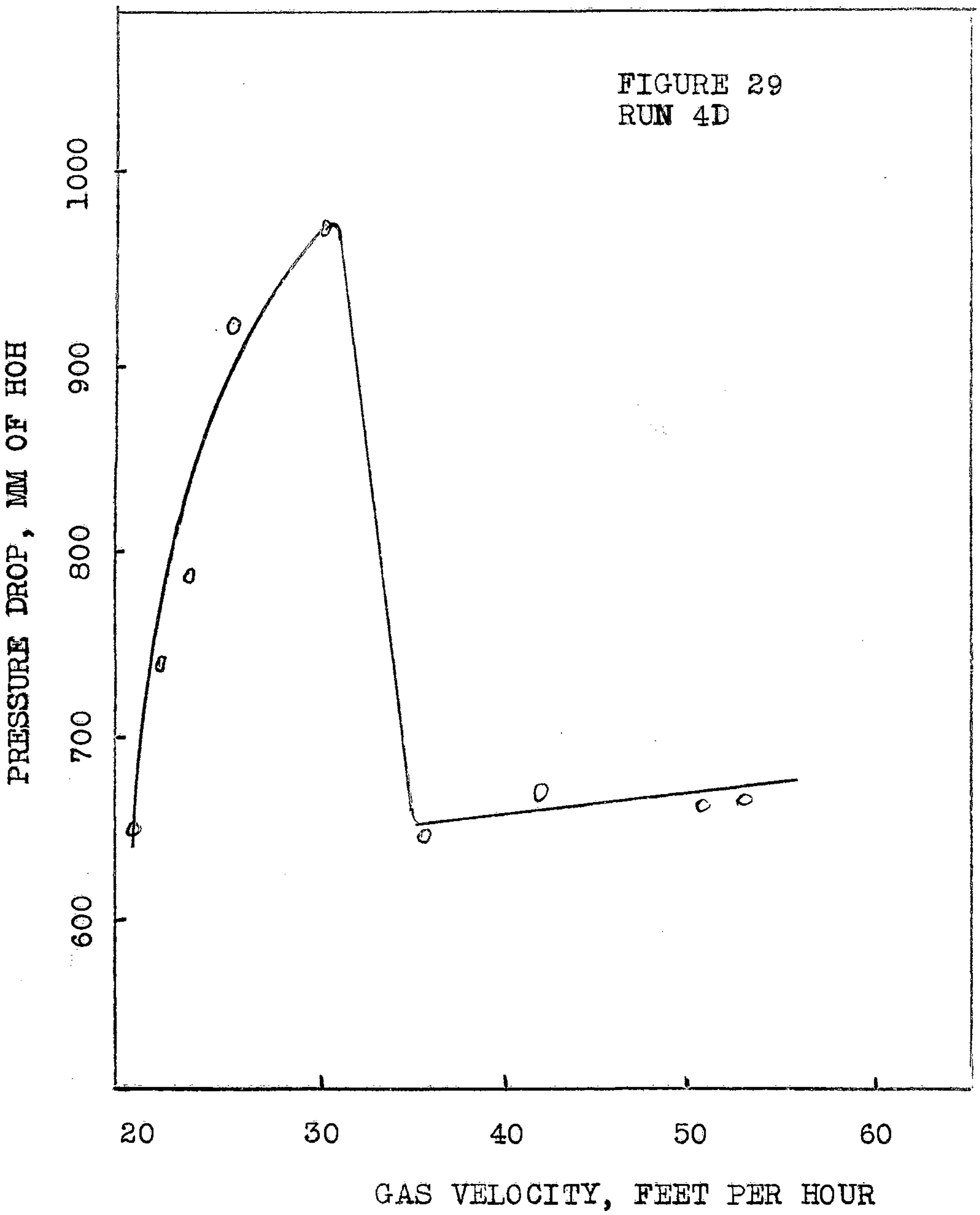


FIGURE 29
RUN 4D
PRESSURE DROP, MM OF HOH
1000
900
800
700
600
20
30
40
50
60
GAS VELOCITY, FEET PER HOUR

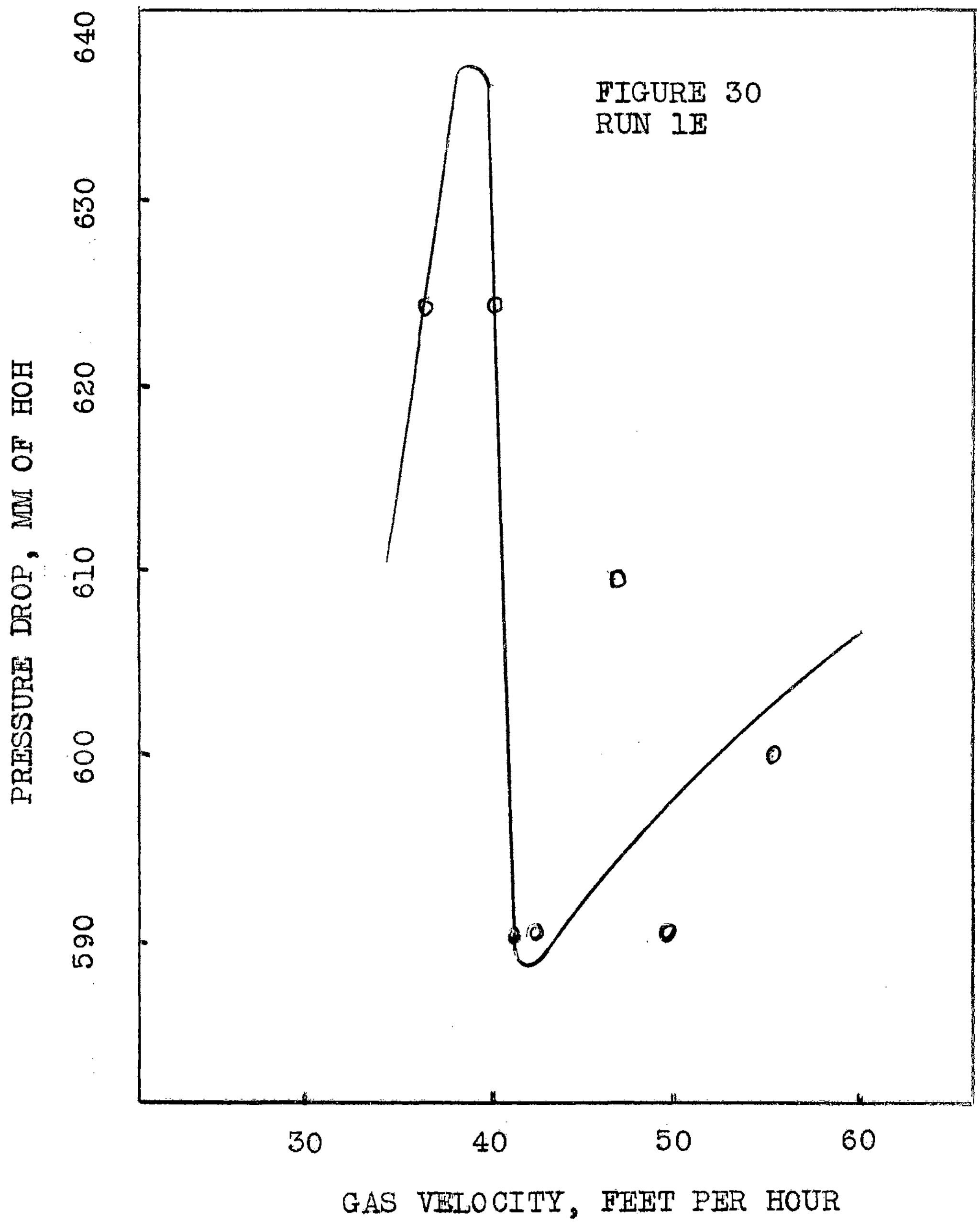


FIGURE 30
RUN 1E
PRESSURE DROP, MM OF HOH
640
630
620
610
600
590
30
40
50
60
GAS VELOCITY, FEET PER HOUR

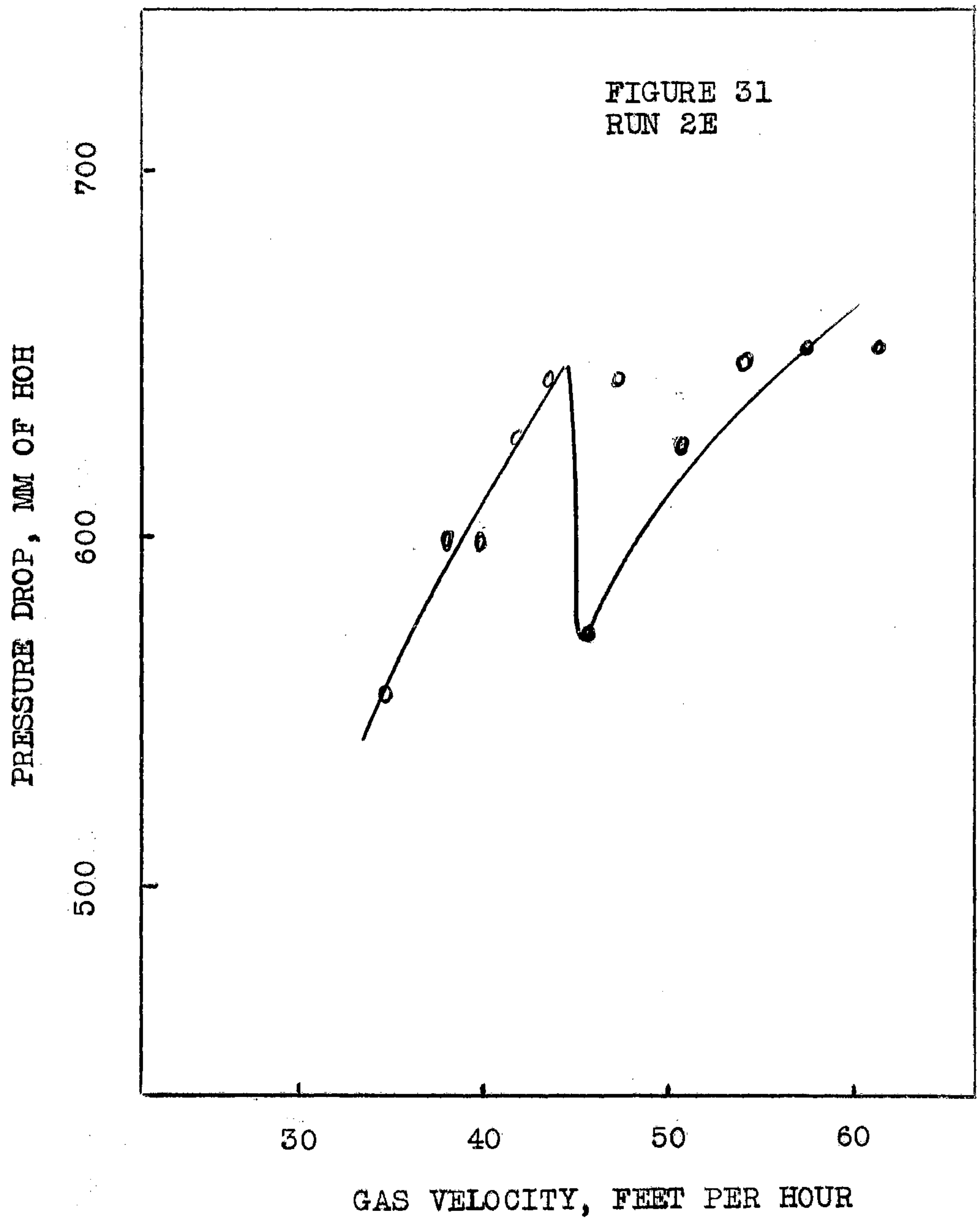


FIGURE 31
RUN 2E
PRESSURE DROP, MM OF HOH
700
600
500
30
40
50
60
GAS VELOCITY, FEET PER HOUR

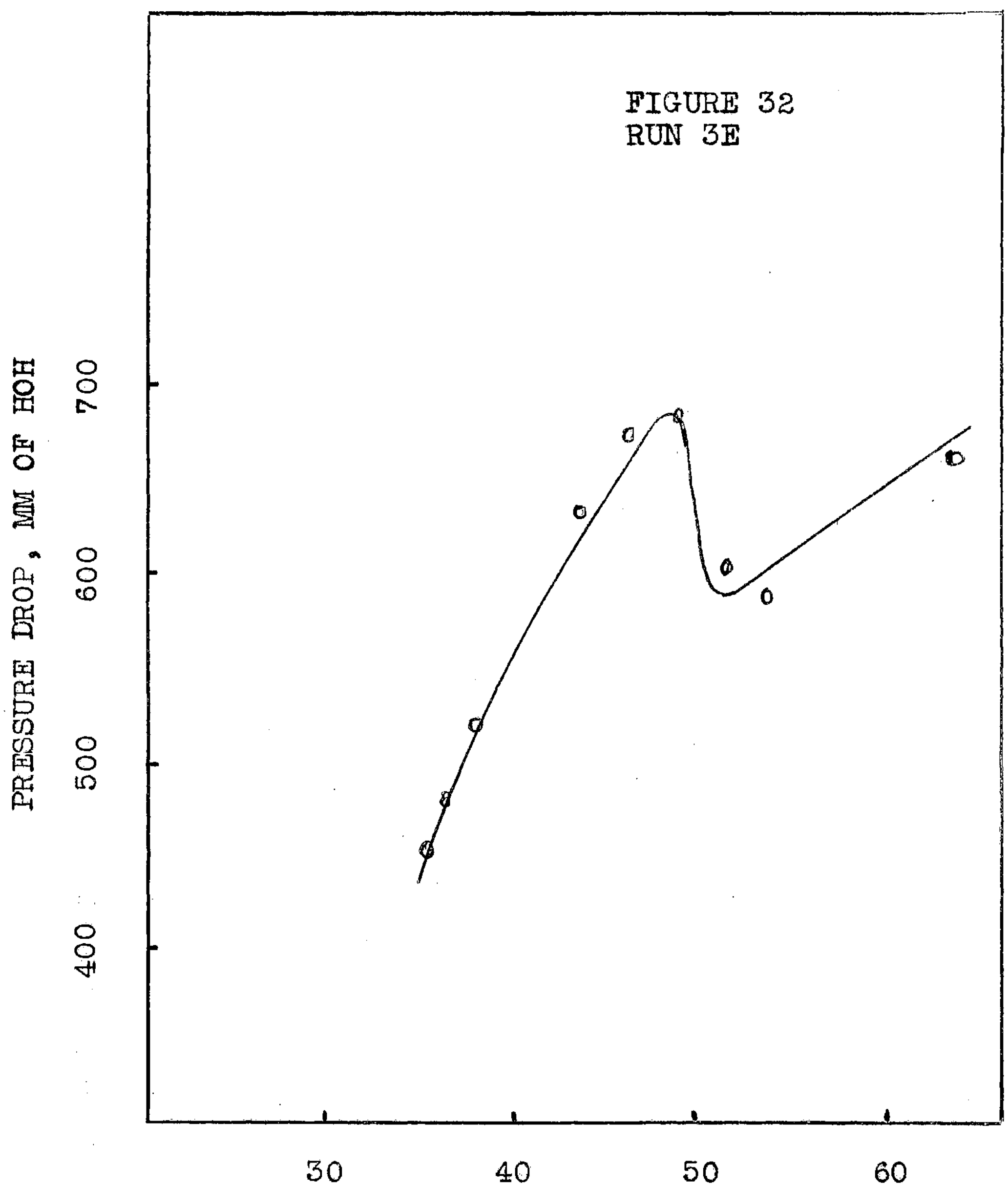


FIGURE 32
RUN 3E
PRESSURE DROP, MM OF HOH
700
600
500
400
30
40
50
60

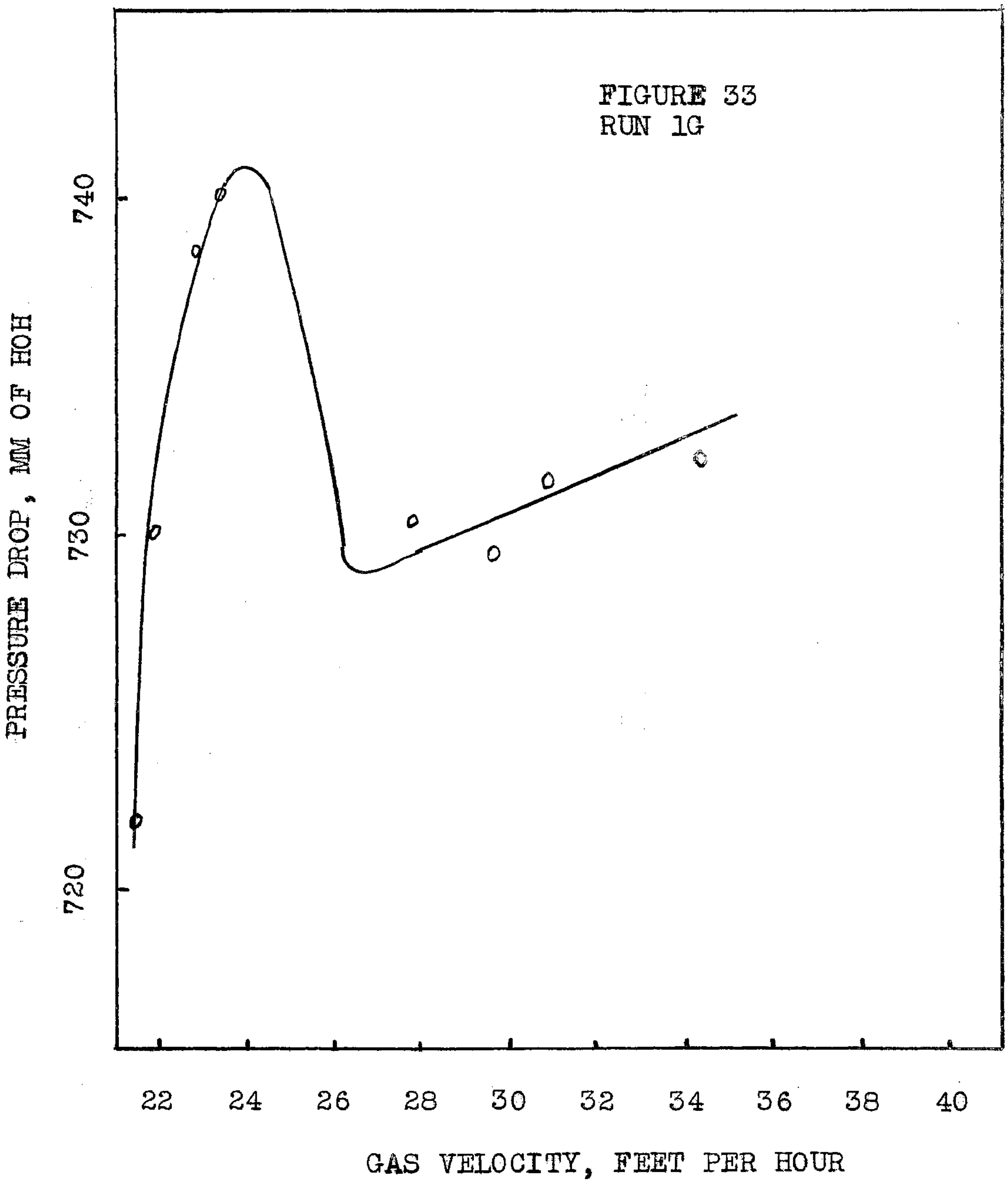


FIGURE 33
RUN 1G
PRESSURE DROP, MM OF HOH
740
730
720
22
24
26
28
30
32
34
36
38
40
GAS VELOCITY, FEET PER HOUR

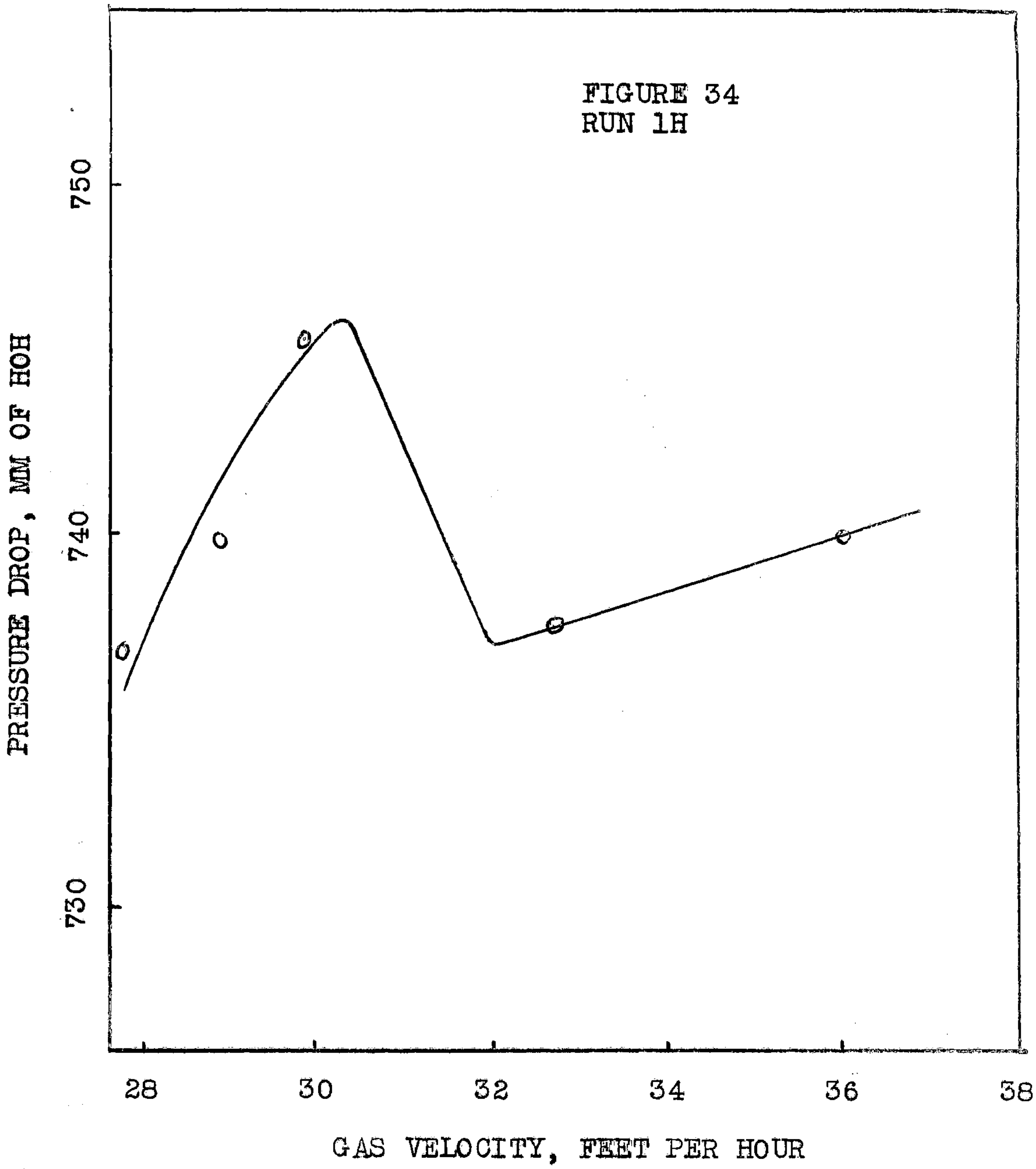


FIGURE 34
RUN 1H
PRESSURE DROP, MM OF HOH
750
740
730
28
30
32
34
36
38
GAS VELOCITY, FEET PER HOUR

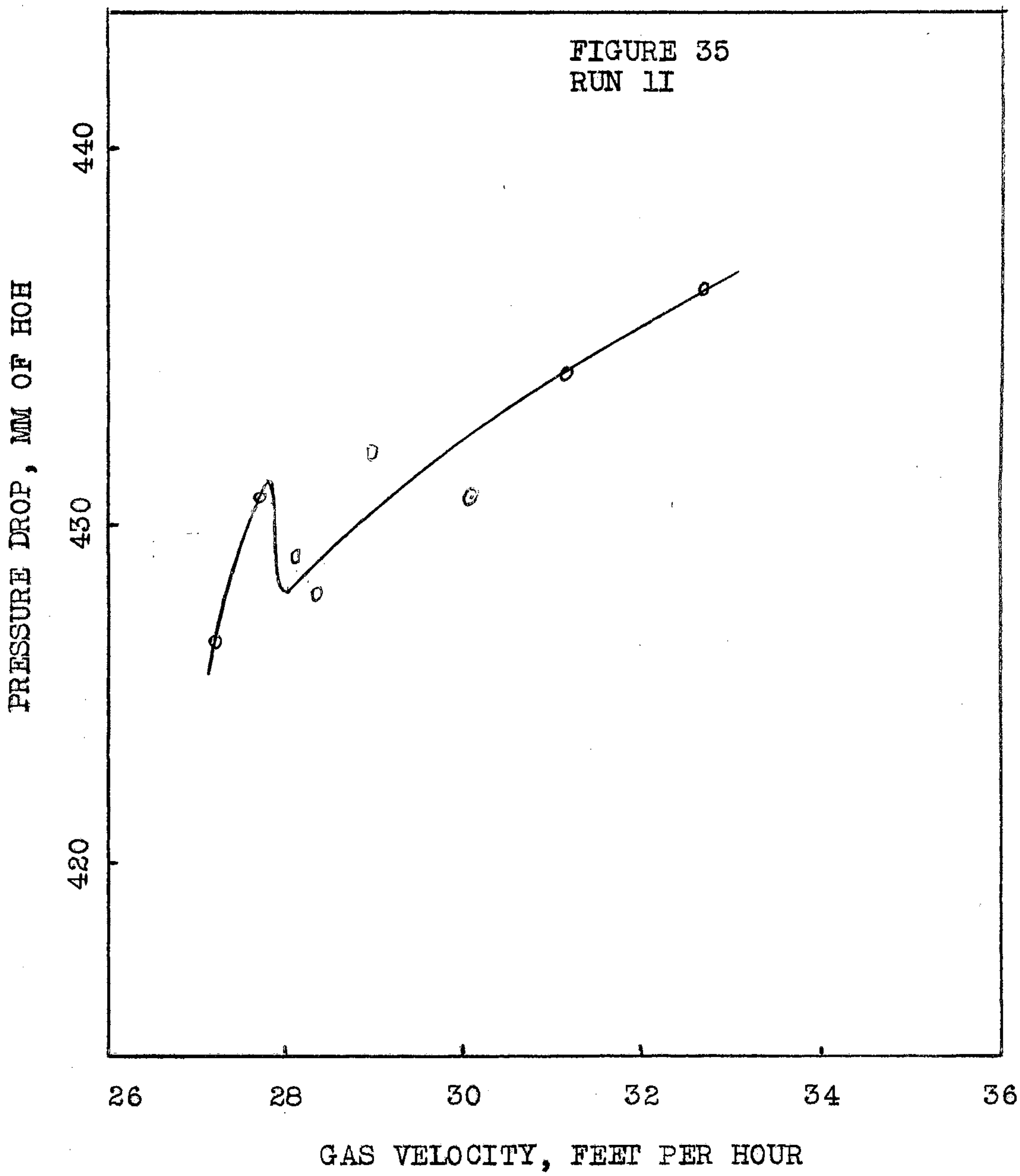


FIGURE 35
RUN 11
440
430
420
PRESSURE DROP, MM OF HOH
26
28
30
32
34
36
GAS VELOCITY, FEET PER HOUR

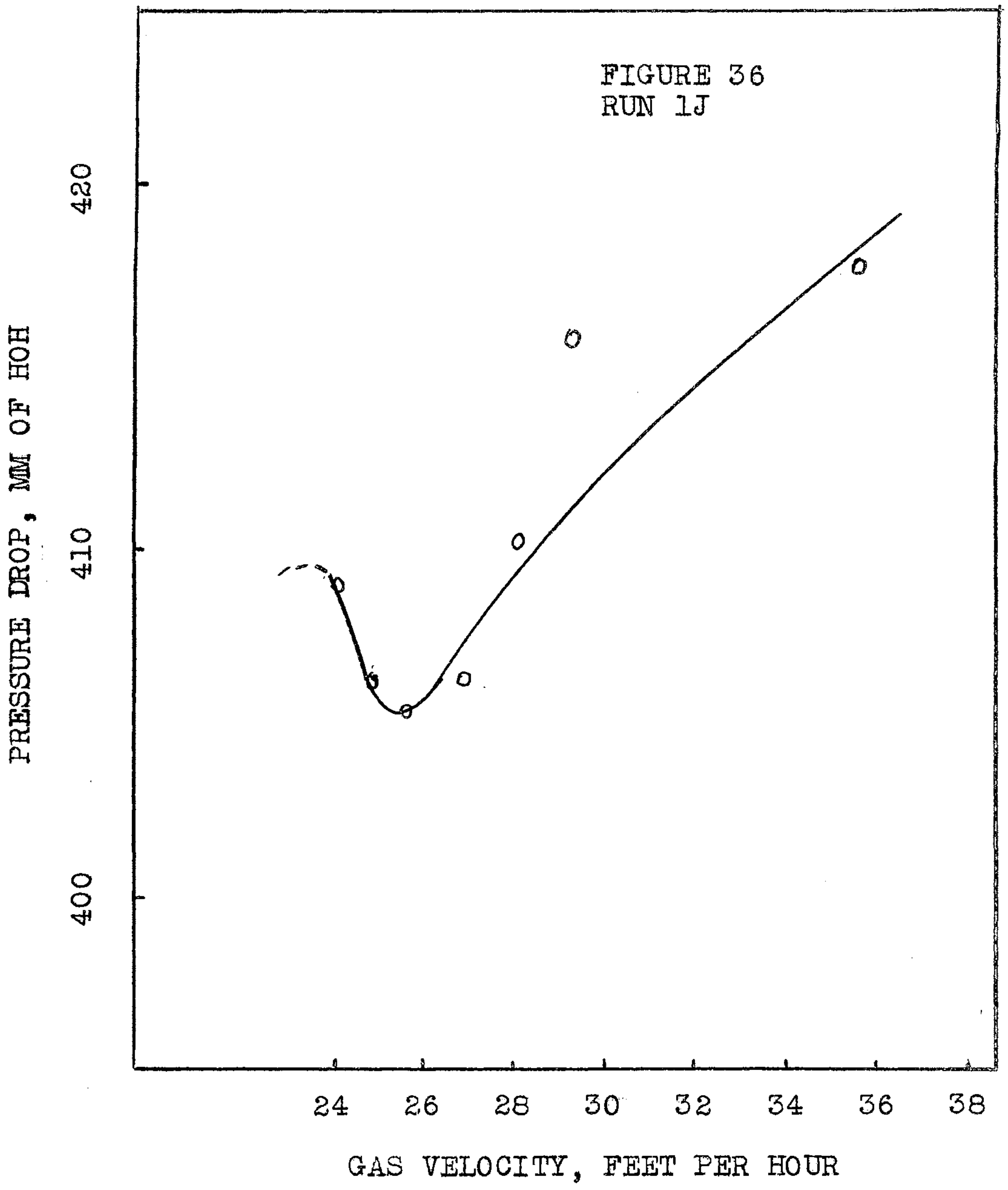


FIGURE 36
RUN 1J
PRESSURE DROP, MM OF HOH
400
410
420
24
26
28
30
32
34
36
38
GAS VELOCITY, FEET PER HOUR

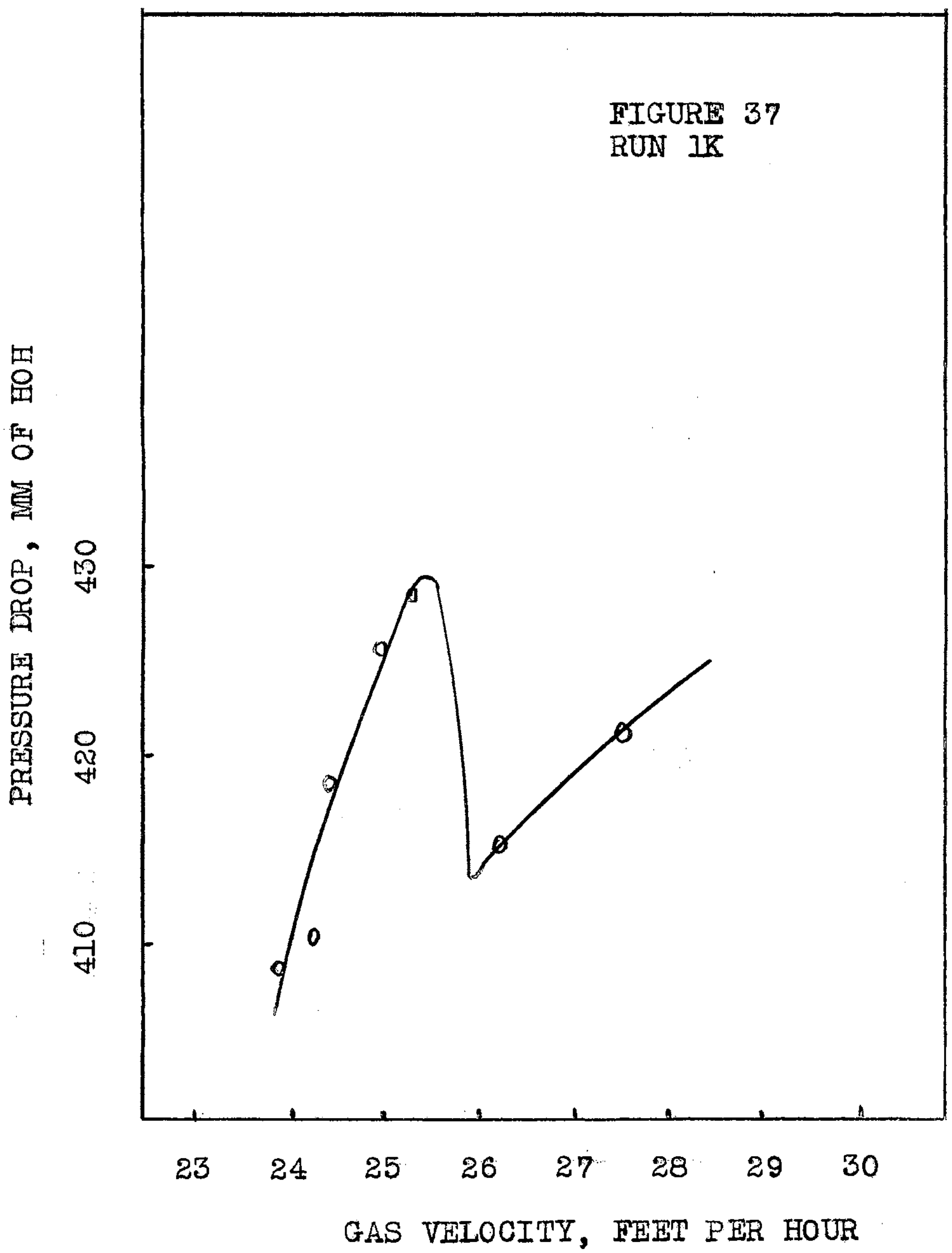


FIGURE 37
RUN 1K
PRESSURE DROP, MM OF HOH
410
420
430
23
24
25
26
27
28
29
30
GAS VELOCITY, FEET PER HOUR

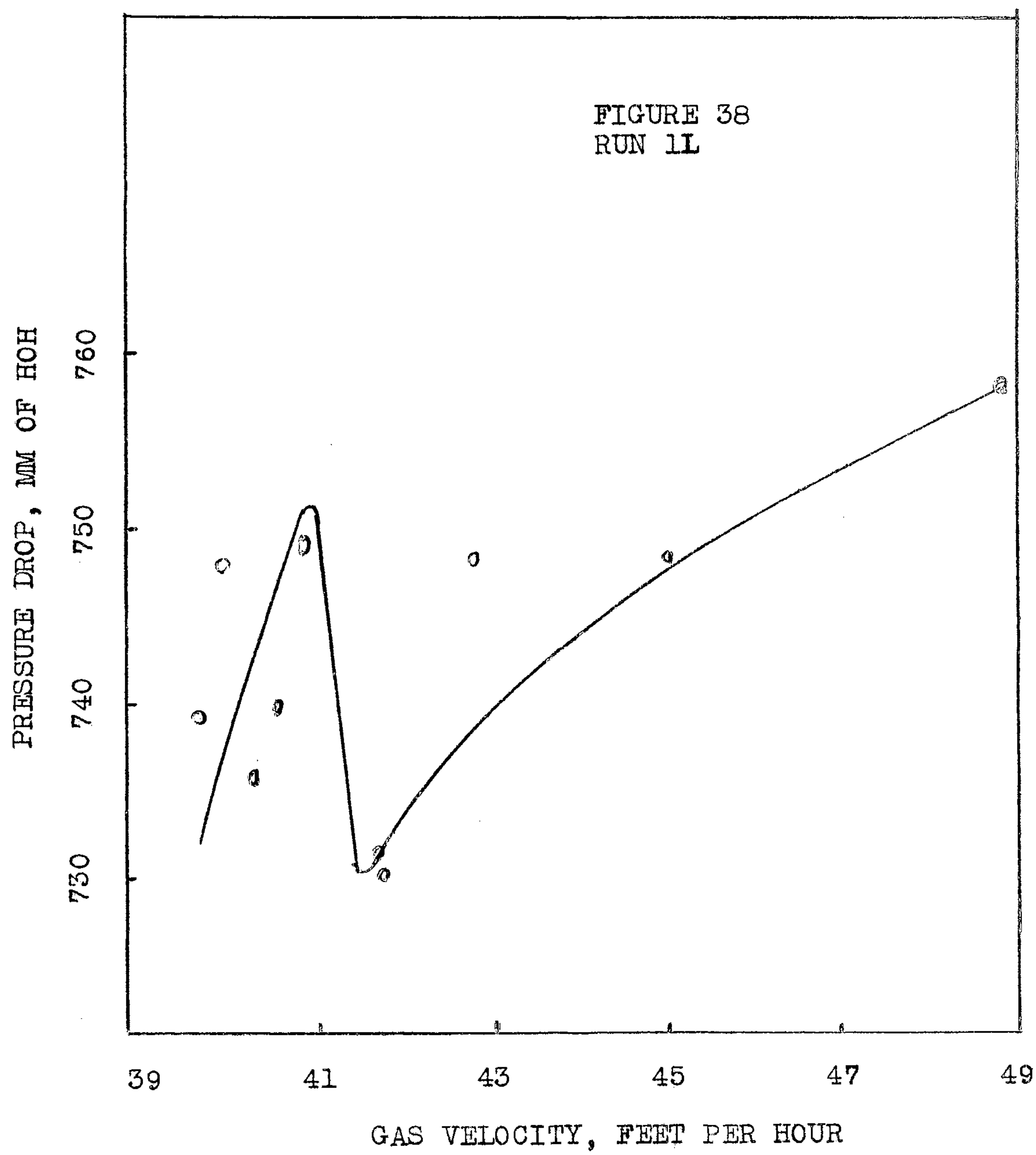


FIGURE 38
RUN 1L
PRESSURE DROP, MM OF HOH
730
740
750
760
39
41
43
45
47
49
GAS VELOCITY, FEET PER HOUR

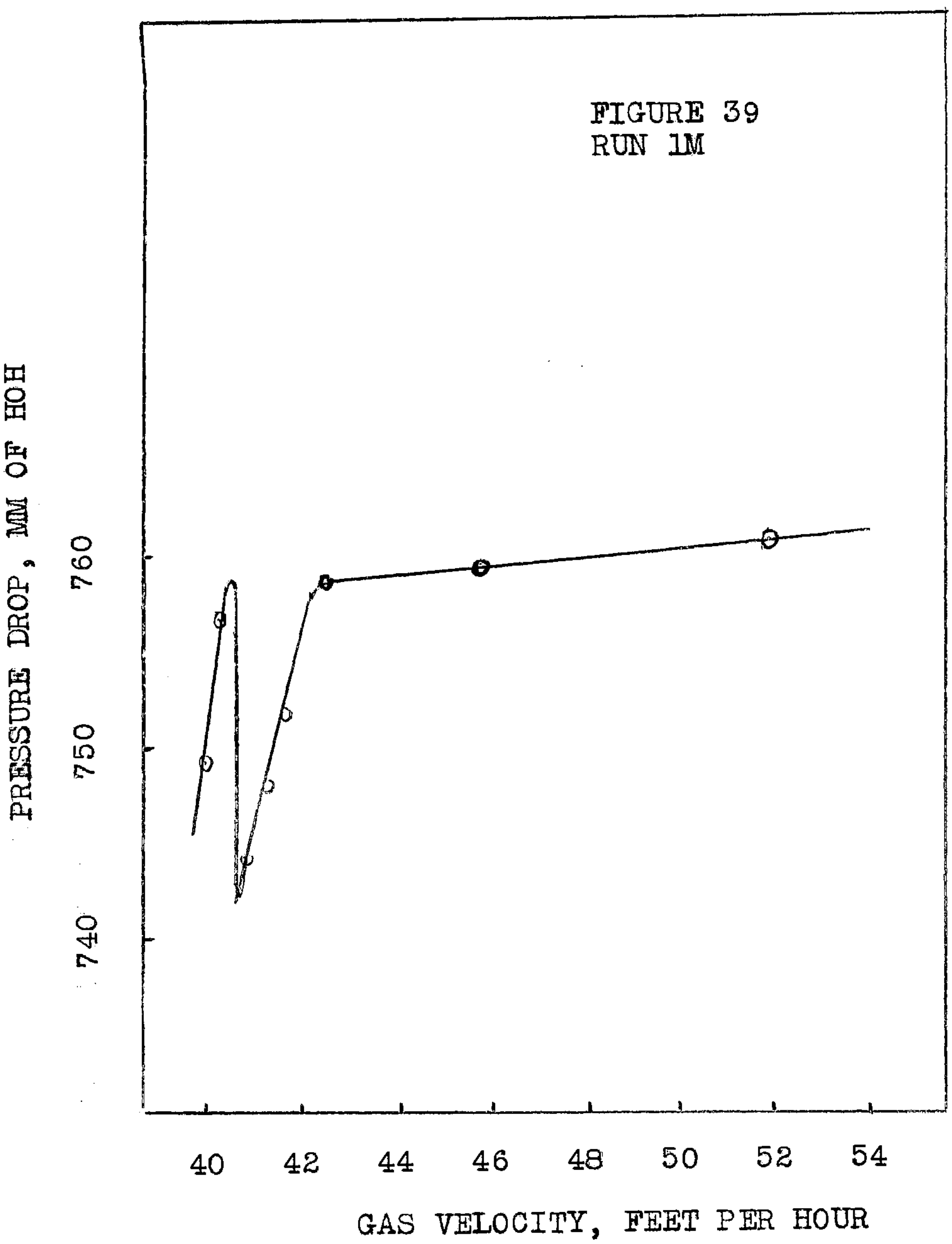


FIGURE 39
RUN 1M
PRESSURE DROP, MM OF HOH
760
750
740
40
42
44
46
48
50
52
54
GAS VELOCITY, FEET PER HOUR

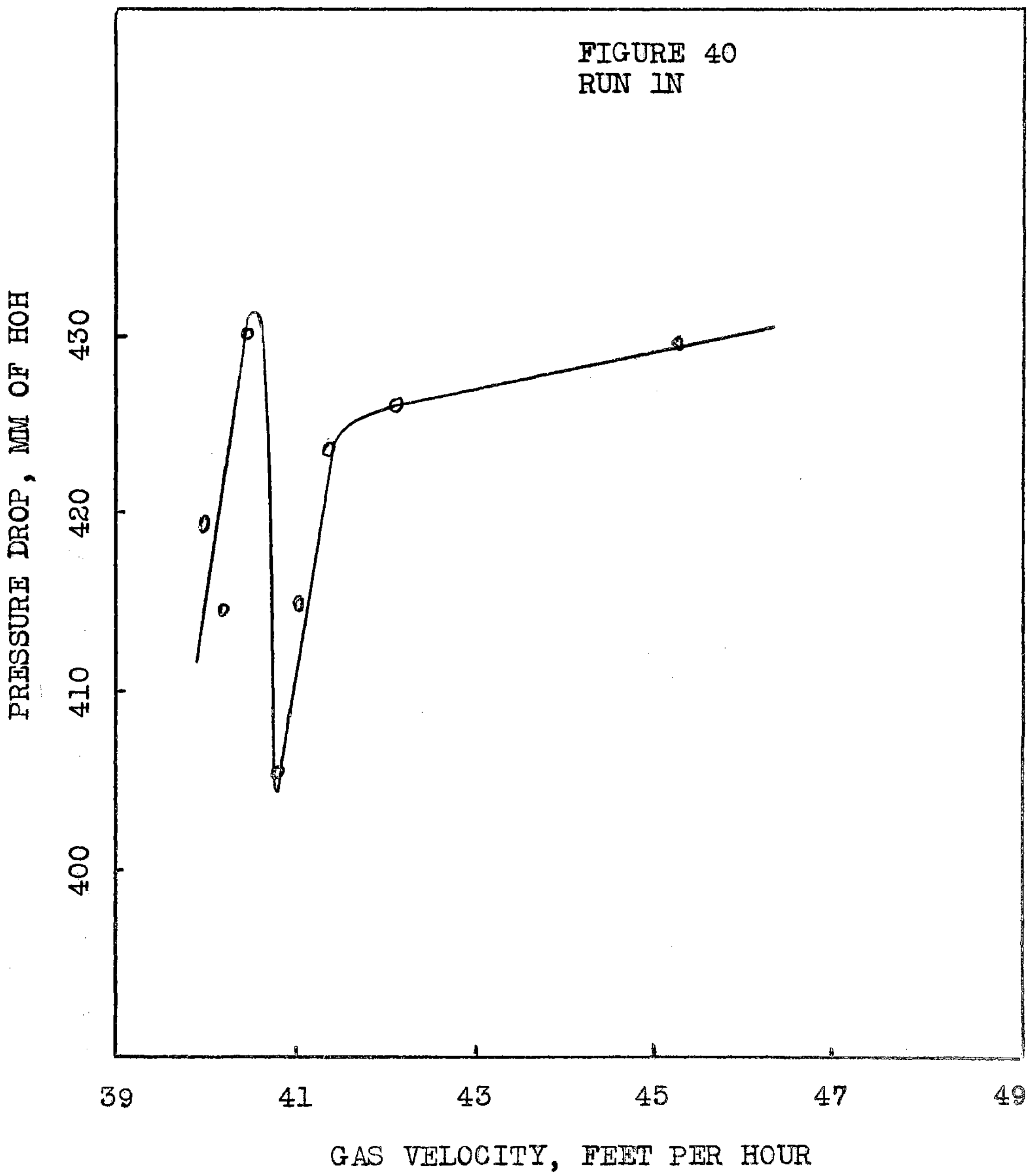


FIGURE 40
RUN 1N
PRESSURE DROP, MM OF HOH
430
420
410
400
39
41
43
45
47
49
GAS VELOCITY, FEET PER HOUR

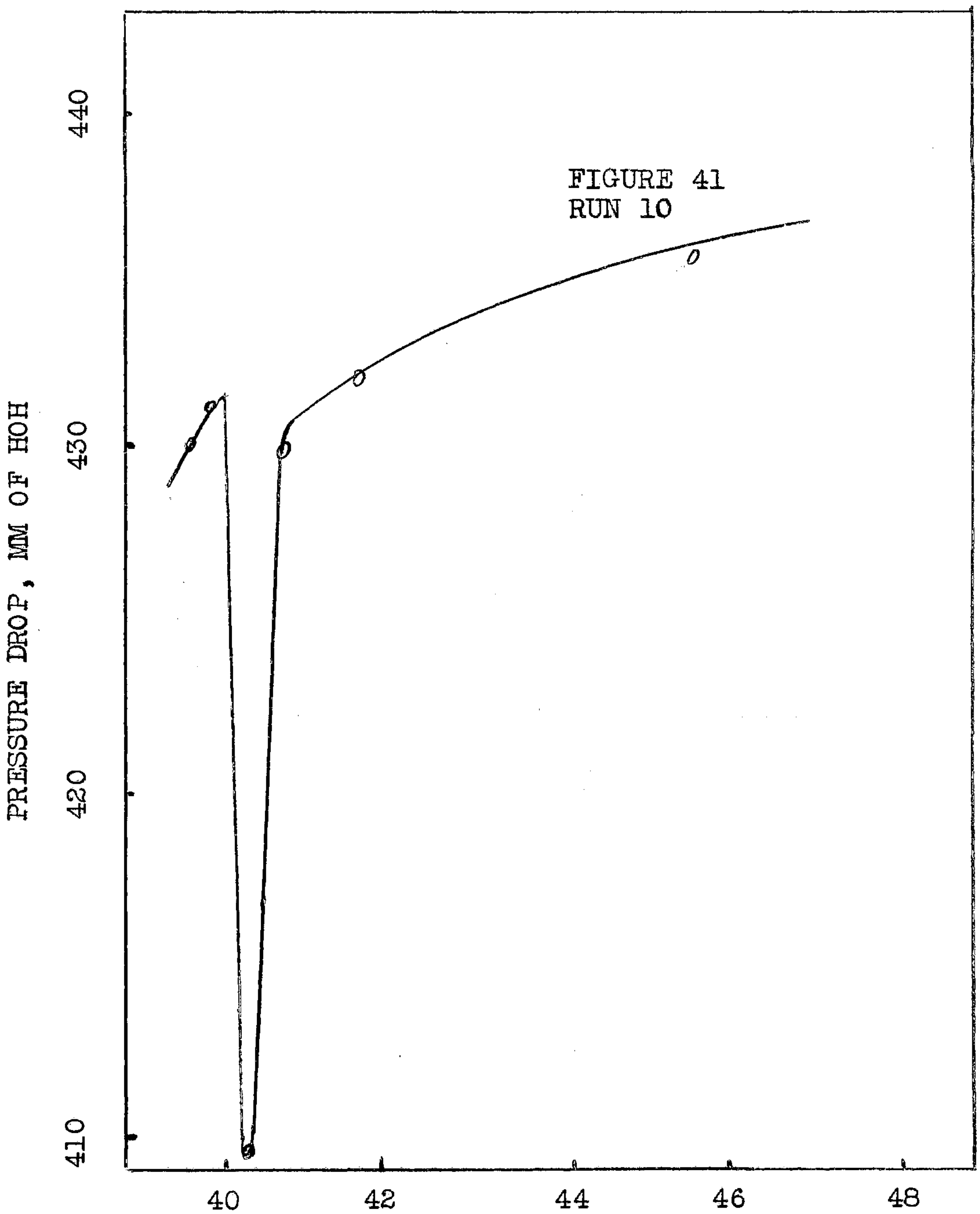


FIGURE 41
RUN 10

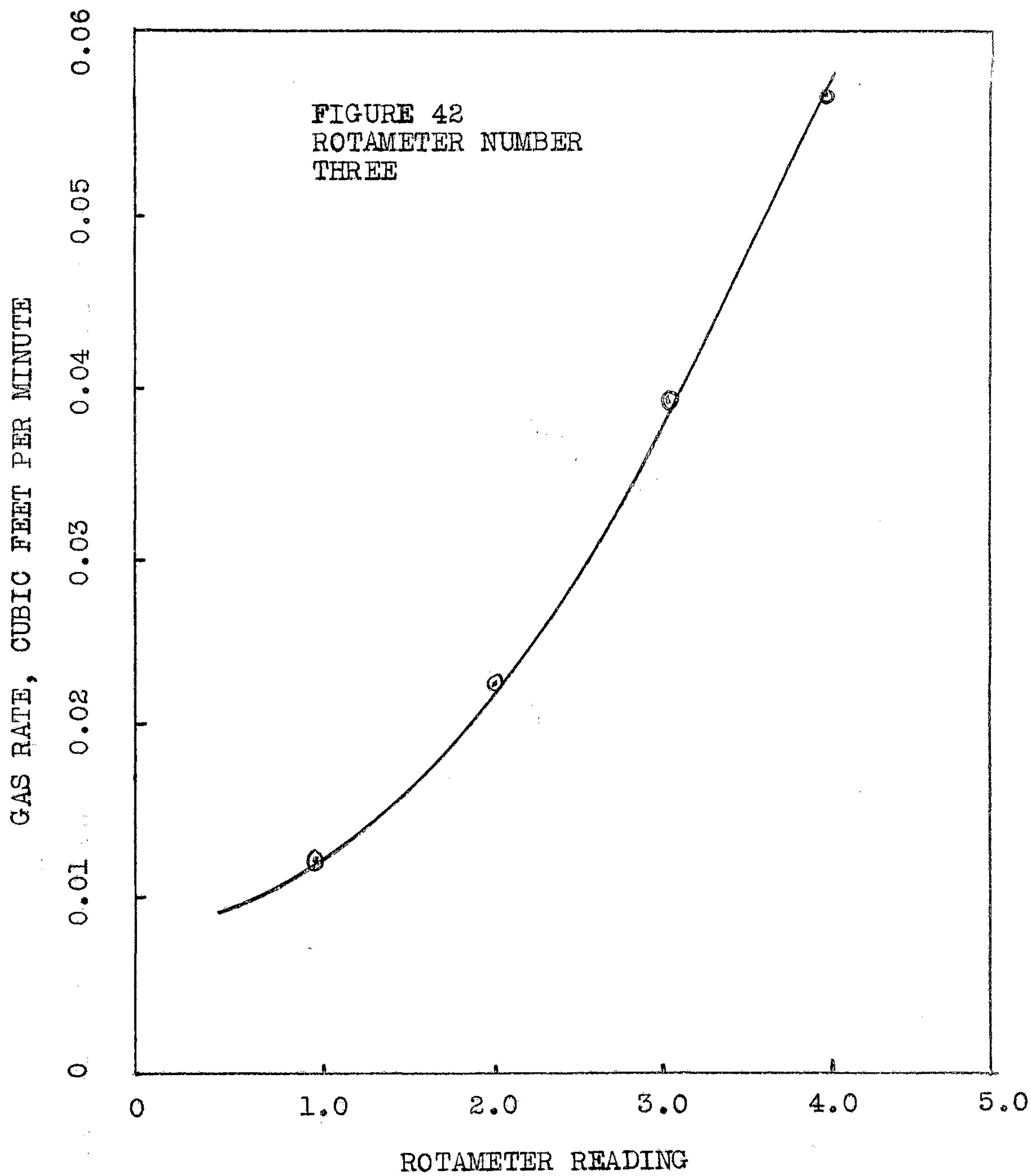


FIGURE 42
ROTAMETER NUMBER
THREE
GAS RATE, CUBIC FEET PER MINUTE
0.06
0.05
0.04
0.03
0.02
0.01
0
0
1.0
2.0
3.0
4.0
5.0
ROTAMETER READING

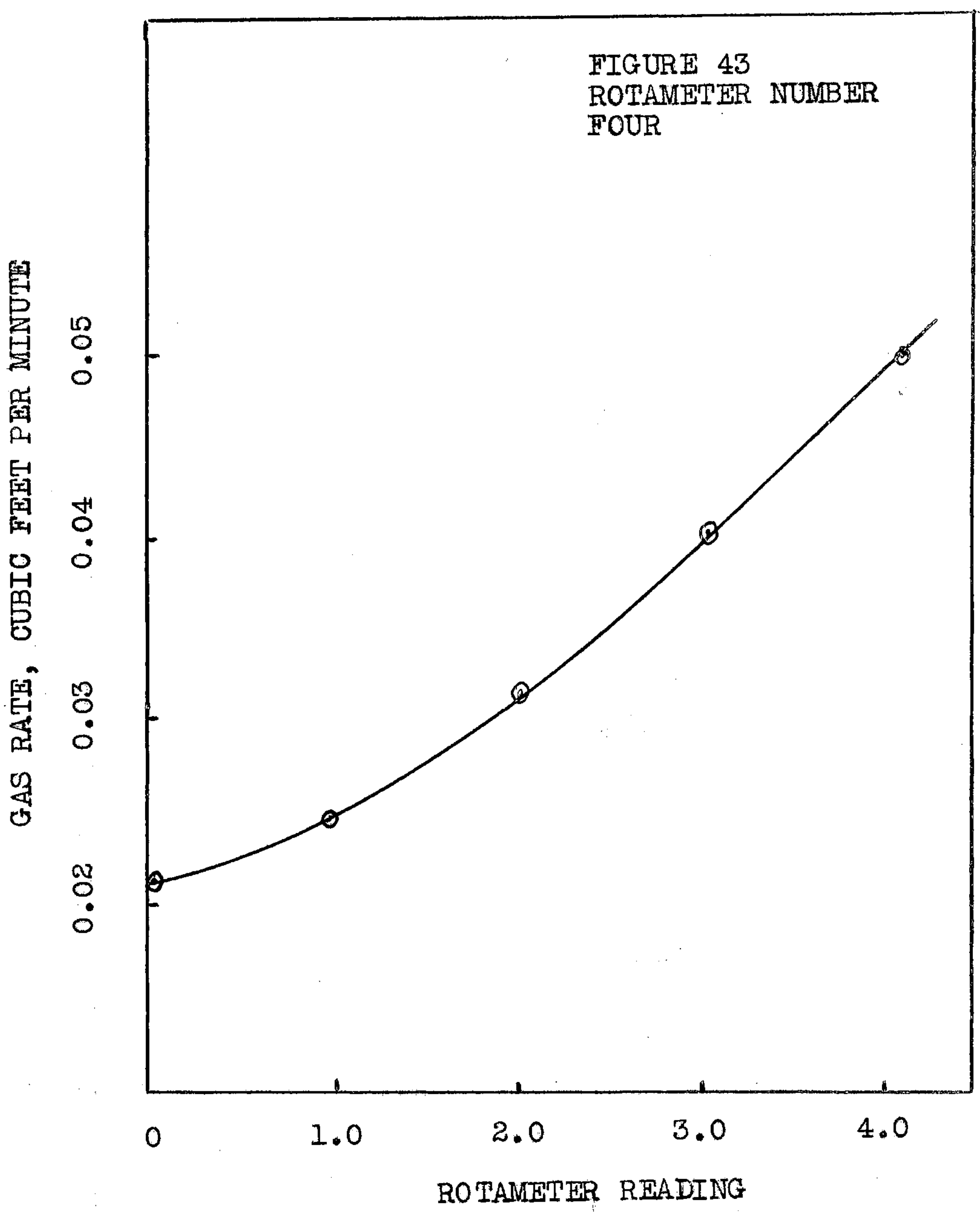


FIGURE 43
ROTAMETER NUMBER
FOUR
GAS RATE, CUBIC FEET PER MINUTE
0.02
0.03
0.04
0.05
0
1.0
2.0
3.0
4.0
ROTAMETER READING

VITA

James Mathias Weber

Candidate for the Degree of

Master of Science

Thesis: STUDIES IN FLUIDIZATION

Major Field: Chemical Engineering

Biographical:

Personal data: Born in Oklahoma City, Oklahoma, July 7, 1930, the son of Max M. and Catherine Jones Weber.

Education: Attended grade school in Birmingham and Lipscomb, Alabama; was graduated from West End High School in Birmingham in 1948; received the Bachelor of Science degree from the Alabama Polytechnic Institute with a major in Chemical Engineering in June, 1951; completed requirements for the Master of Science Degree in May, 1959.

Professional experience: Worked with Phillips Petroleum Company in Bartlesville, Oklahoma, as a Research Engineer from June, 1951, until September, 1955; is presently employed by the Dow Chemical Company in Freeport, Texas, as a Senior Research Engineer.